Anomalous low frequency dissipation in metals

problems and solutions

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LIGO-G1000660
Mitaka, May 27th 2010
Caltech, June 25th 2010

Abstract

It was long understood that the presence of dislocations reduces the material Young's modulus by several percent. It was also well understood that for a given dislocation density in the material the "modulus defect" depends strongly from the average free length of each dislocation between pinning points.

It was well known that dislocation can entangle and effectively pin each other (work hardening is an example).

Nobody realized that during slow transients dislocation dis-entanglement can occur.

Disentanglement of dislocations leads to exotic behaviors like temporary change of resonant frequency, random walk of equilibrium position, in extreme cases spontaneous collapse, very large dissipation while dislocations re-arrange.

We observed a phase transition at low frequency with dislocations acting collectively at low frequency (avalanching) and independently at high frequency.

Several measurements illustrating the above scenario will be shown.

The exotic effect observed have profound implications in the design of seismic attenuation for low frequency GW observatories and for all sort of inertial sensors.

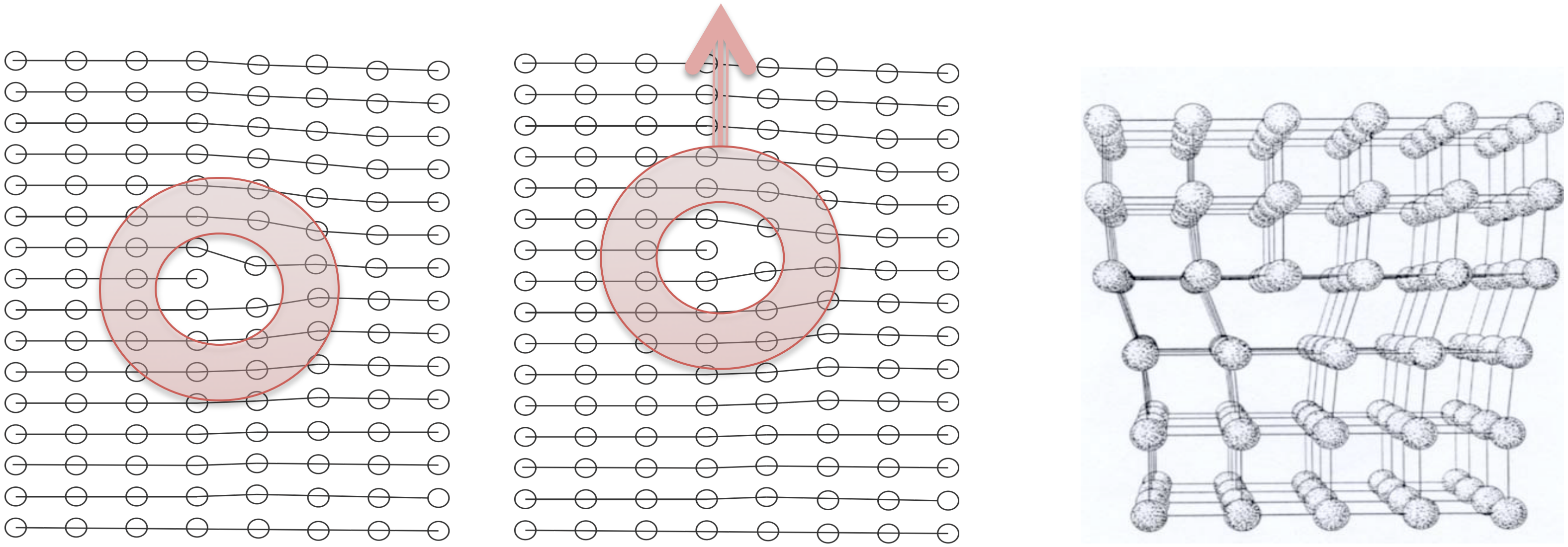
These effects may also affect the present GW detectors. Ideas on how to mitigate these effects are discussed at the end.

OUTLINE

- Theory
  - Dislocation and dissipation, hystorical review
  - Individual vs. Collective dislocations movement
  - Self Organized Criticality (SOC)
- Experimental method
  - What is a GAS filter, why did we use it
- Data analysis and results
  - Hysteresis
  - Low frequency instability
  - Q factor measurements
  - Dissipation dependence from amplitude
  - Frequency dependence from amplitude
  - GAS transfer function
- Conclusions
- Future work

Dislocations basics

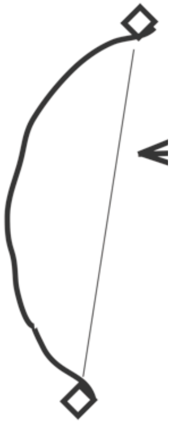
- Dislocations (line, screw) are crystal linear defects.
- they can move “almost” freely through a “zipper” effect (switching the covalent bonds of metals costs no energy)
- They are Pushed by moving stress gradients,



- They are voids in crystal that cost energy (=> they repel)

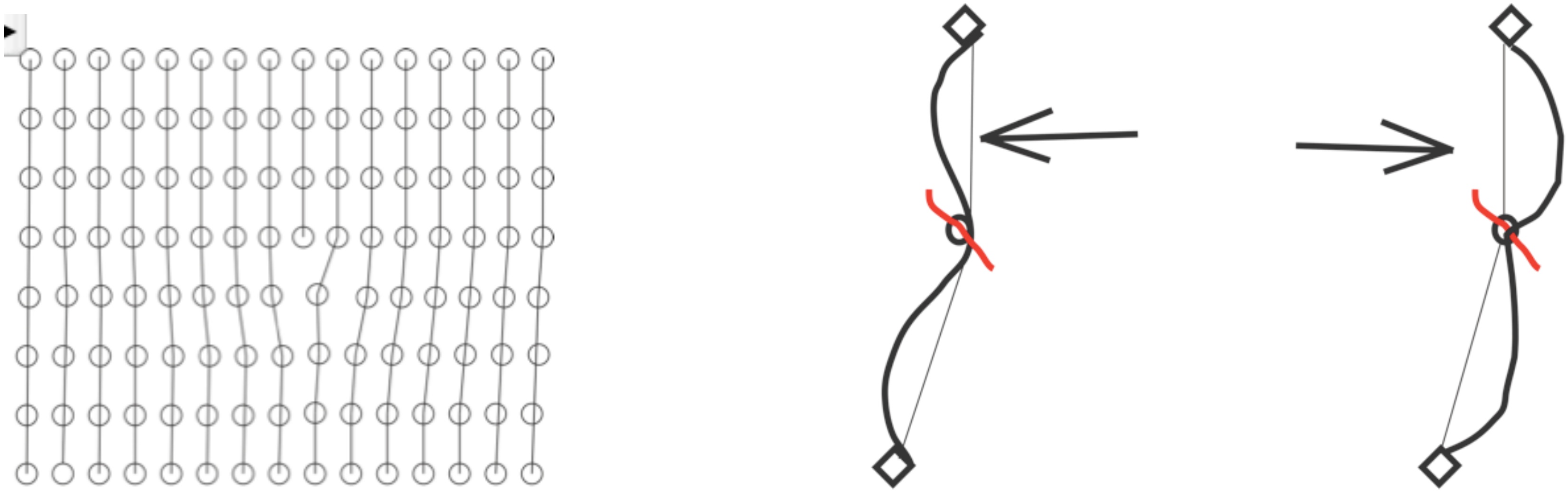
Dislocations basics

- Dislocations cannot end inside crystal (simple topological arguments)
- Extend across the entire grain or form closed loops
- Mostly move rather freely across crystal
- Get pinned at various intervals by
  - point defects like impurities, atomic vacancies, …
  - Other dislocations



Dislocations *(established facts)*

- It is well established that dislocations are at the base of dissipation in metals
- Dislocations dissipate by drifting with delay under oscillating stress and forming arches



A. Granato, et al., “Theory of mechanical damping due to dislocations”, Jour. Of Appl. Phys., vol 27, n 6, p583-593, 1956

Dislocations *(established facts)*

- More dislocations / cm^3 => More dissipation
- Thousands of km of dislocation/ cm^3 in carefully grown monocrystals with negligible work hardening (>1/um^2)
- Orders of magnitude more in polycrystalline samples (stress of freezing, austenitic to martensitic transitions, lamination processes, machining)

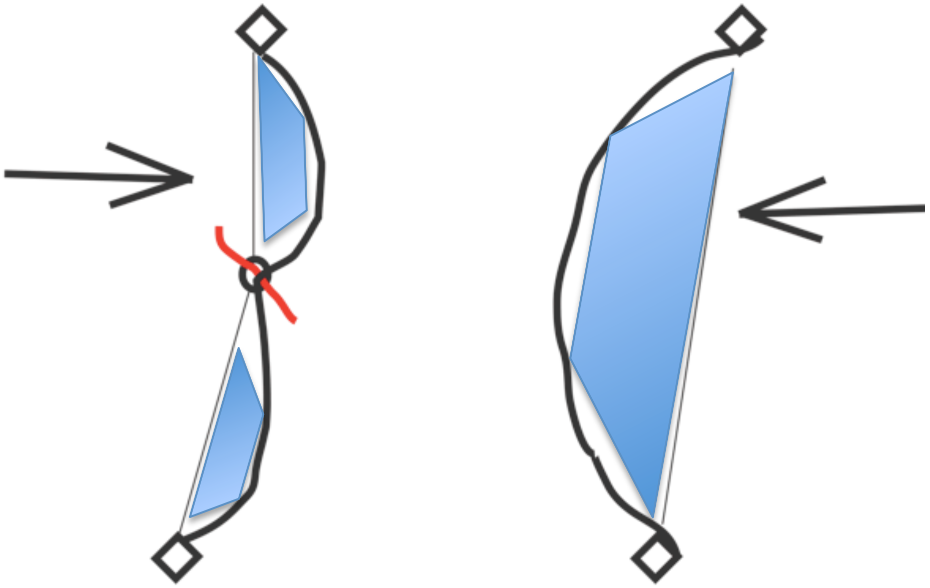
D.O. Thompson, D.H. Holmes, “The effects of neutron irradiations on the young’s modulus of copper single crystals”, Jour. Appl. Phys., **27**-7, p 713-723, 1956

- At equal density of dislocation per cm^3 longer free segments move more,

  span over <u>larger areas</u> and

  generate <u>more dissipation</u>
- Anchoring points of any kind reduce the average free length

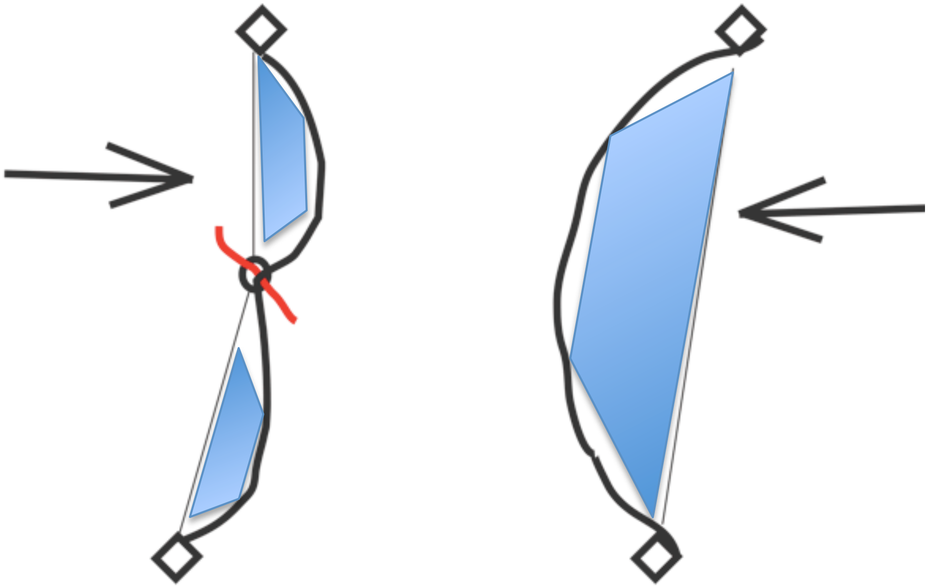
  and the dissipation.



- Dissipation ~l^4

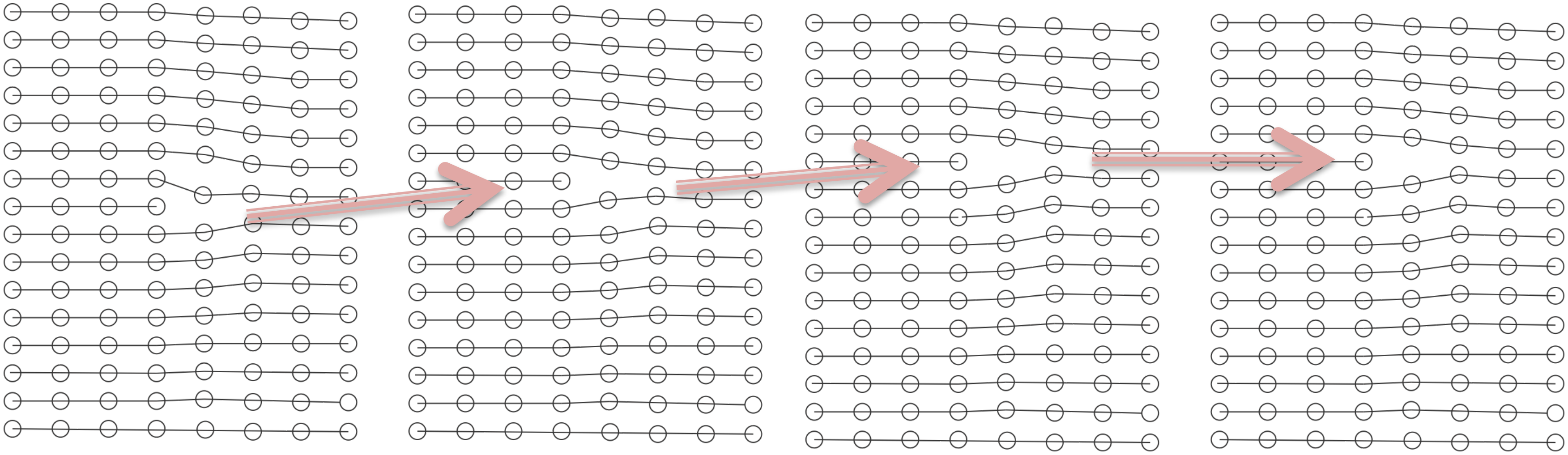
Nowick A S and Berry B S *Anelastic Relaxation in Crystalline Solids,* (New York: Academic) 1972

- Movement of dislocations generate Yield
- Young’s modulus drops in presence of dislocations   > 20% observed
- The material yield more for same stress field with more and longer dislocation
- ➔
- Modulus defect $\sim l^2$

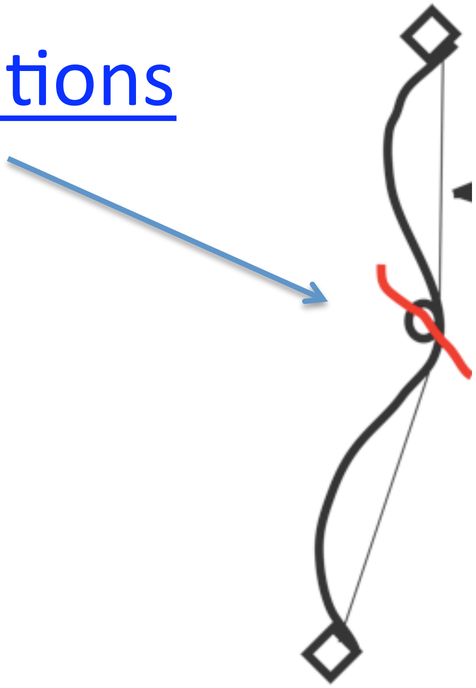


Nowick A S and Berry B S *Anelastic Relaxation in Crystalline Solids,* (New York: Academic) 1972

- Dislocations carry deformation.
- Moving dislocations deform the flexure
- Metastable transport of dislocations change the equilibrium point
  - Static hysteresis



- The free length of dislocation segments is reduced by pinning points, intentionally introduced in the metal grain
- Precipitates, carbon crystals, ...
- Dislocations can pin other dislocations



(➔ the invention of work hardening)

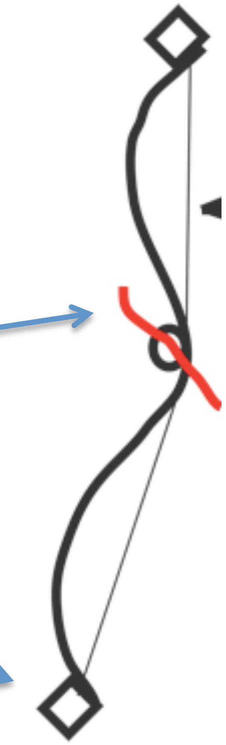
Material less lossy, more elastic

Typical scales

- Few- tens of nm typical distance between dislocations
- Pinning points also spaced at tens of nm
- But point-like
- Dislocations cross entire crystal (um)

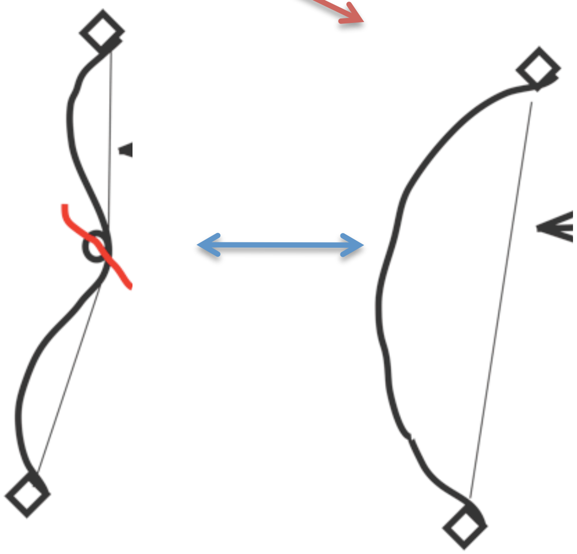
- Can turn around a pinning point
- Cannot turn around other dislocations

- Free length just as likely limited by entanglement than pinning

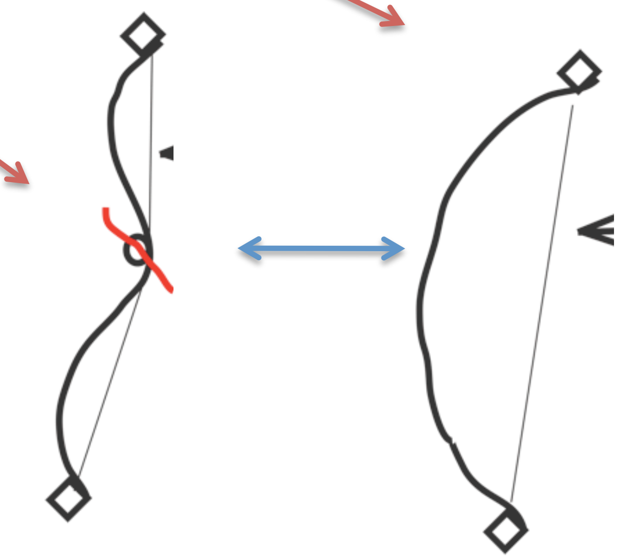


- Dislocations can move, but
- Cannot cross each other (energetically forbidden)
- ➔ therefore will entangle and disentangle
- If entanglement and disentanglement are permitted

- ➔ free length changes



- Dislocations can move, but
- Cannot cross each other (energetically forbidden)
- ➔ therefore will entangle and disentangle
- If entanglement and disentanglement are permitted
- ➔ free length changes
- ➔ Young’s modulus unstable
-

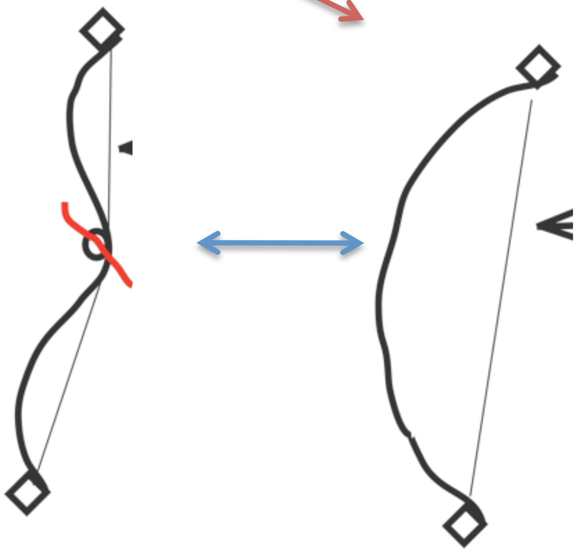


- Dislocations can move, but
- Cannot cross each other (energetically forbidden)
- → therefore will entangle and disentangle
- If entanglement and disentanglement are permitted

- → free length changes

- → Young's modulus unstable

- → Equilibrium point unstable



- Entanglement and disentanglement is an intrinsically slow process
- Many dislocations must drift sequentially
- Long time constants predicted
- Avalanching is predicted
- It can even be self triggering

- At low frequency
  - Restoring forces are weak
- dynamic disentanglement

  can be expected to have

  dramatic effects !

SOC theory

- Entangled dislocations act collectively
- We observed a LF Dissipation Phase Transition From a regime in which
- Individual dislocation motion dominates
  - With “viscous” or “structural” damping
- To an avalanche dominated Regime controlled by Self Organized Criticality
  - States and rules

Per Bak 1996
How nature works:
The Science of Self-Organized Criticality

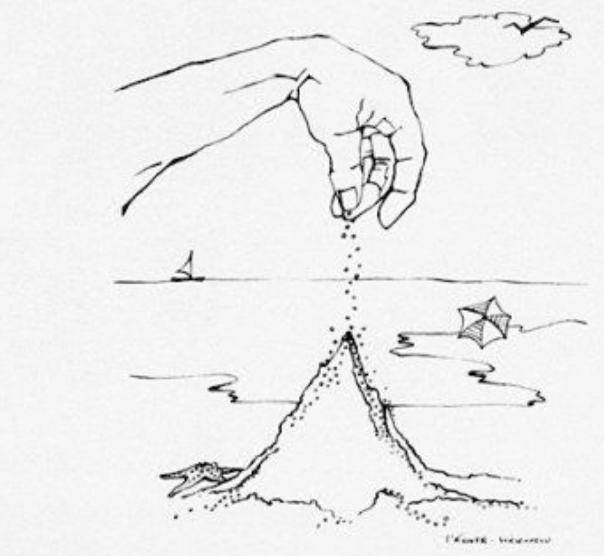


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

SOC theory

- Self Organized Criticality mode (avalanches)

  Means
- Hysteresis, random walk
- Changes of Young’s modulus
- Dramatic change of dissipation

Other Predictions:

- Excess LF and 1/f noise
- Reduced attenuation power

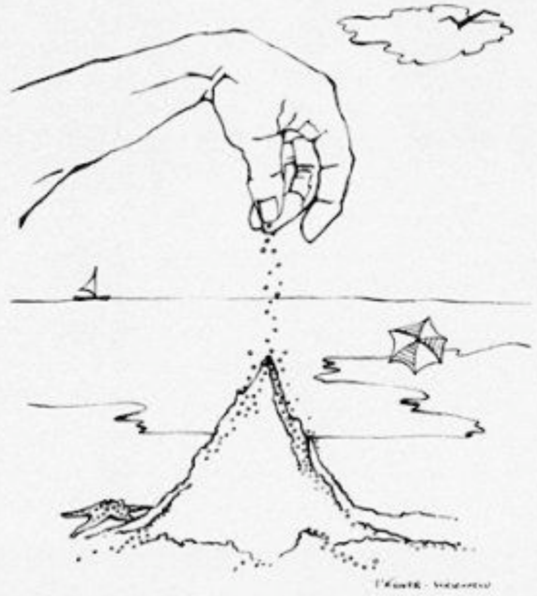


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

Per Bak 1996
How nature works:
The Science of Self-Organized Criticality

Self Organized Criticality

(SOC)

- Movement of entangling dislocations is intrinsically **Fractal**
- => Does not follow our beloved linear rules ! !
- => Avalanches induce random motion
- => 1/f noise to higher frequency

Space scales

- Entanglement and collective dislocation motions can extend beyond crystals, across the entire sample

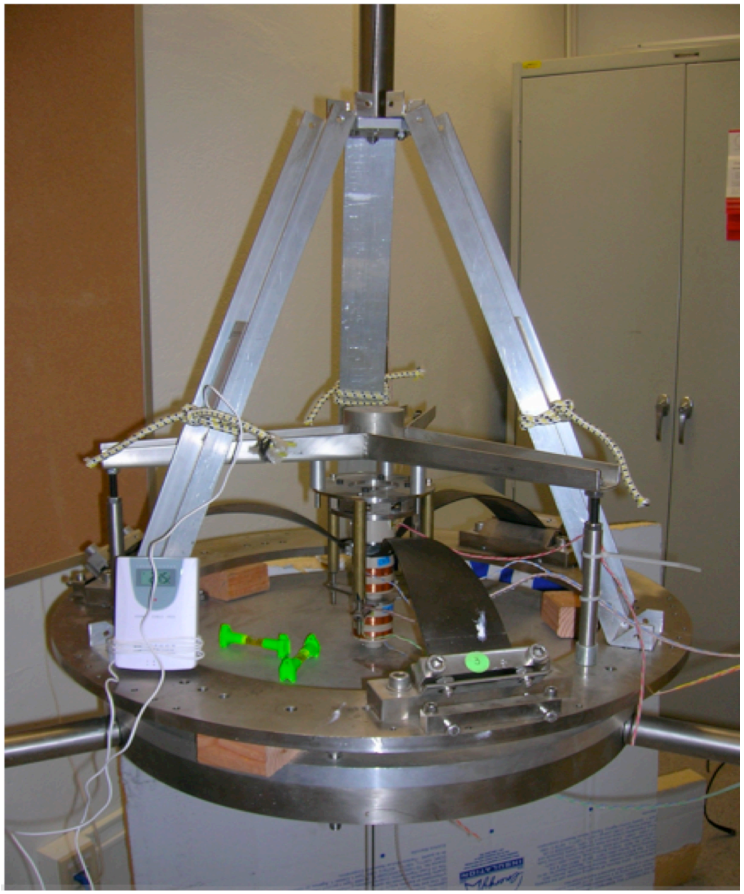
- Avalanches of dislocations can theoretically propagate through the entire sample

- We observe "catastrophic" effects extending across the entire size of the blades, ~38 cm.

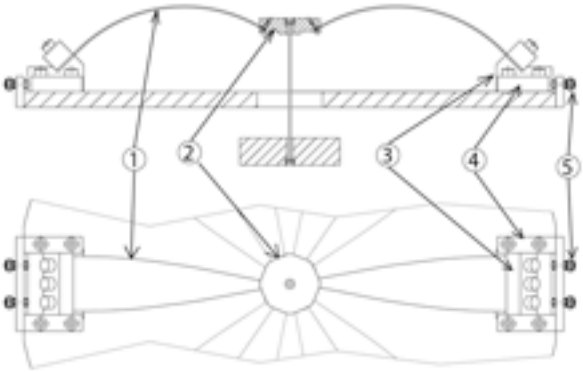
Experimental setup

Experimental setup

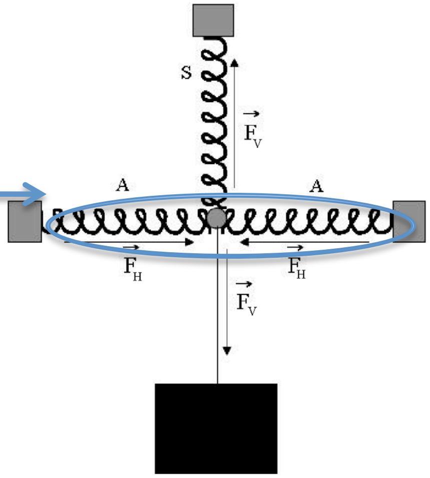
- THE GAS-EMAS filter
- A “microscope” for mesoscale effects

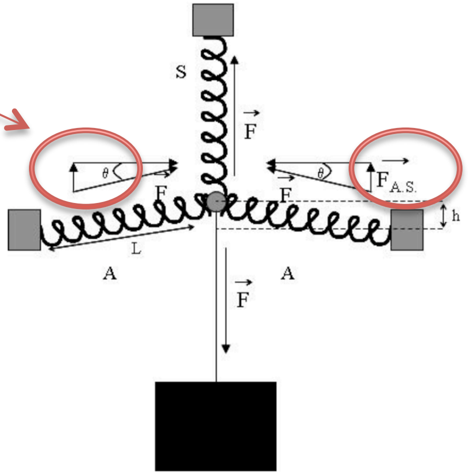


The Geometric Anti Spring (GAS) mechanism



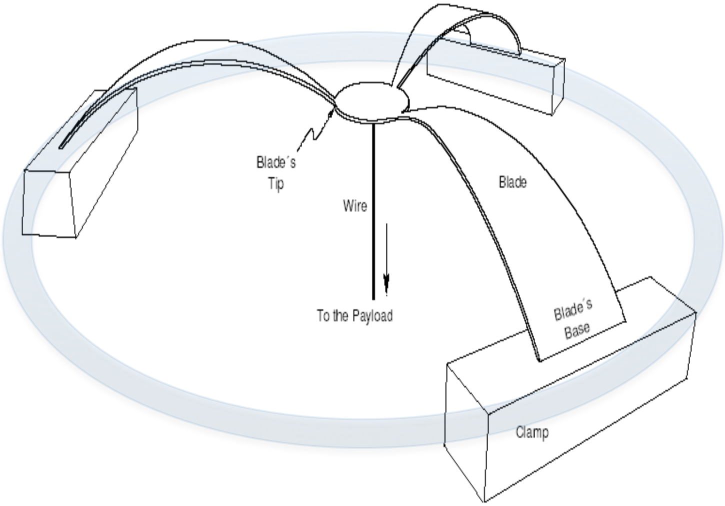
- Arched blades support the load
- Pushing the blades against each other generate a nulled repulsion force
- Vertical movement cause a vertical component to appear, proportional to displacement
- $F = k \, x$
- like a spring but with the sign +



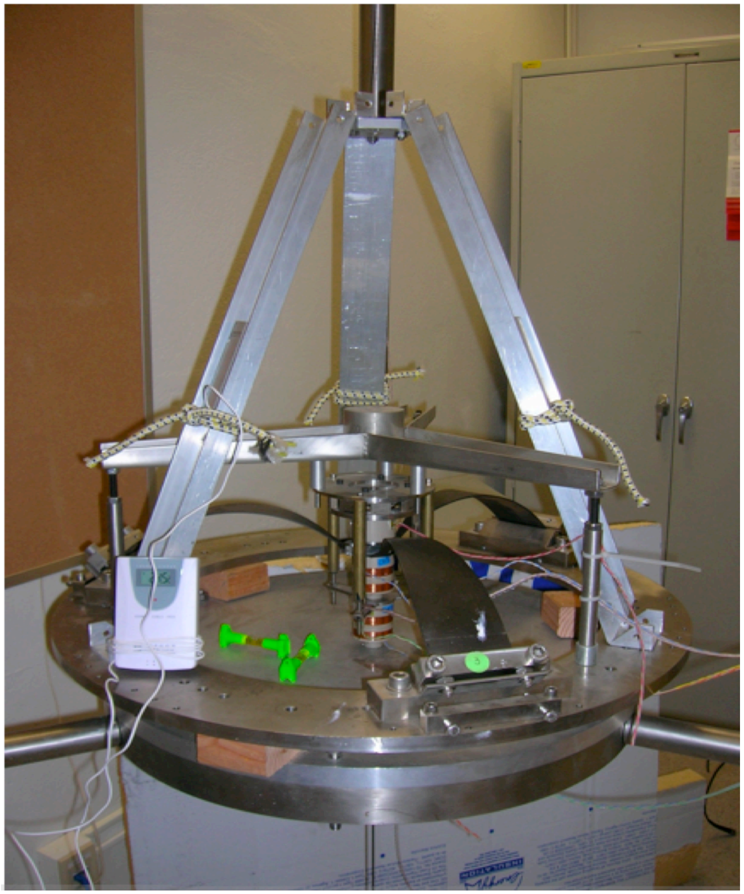


The GAS mechanism

(Geometric Anti Spring)



Radially-arranged Maraging blades clamped to a frame ring.



The GAS mechanism nulls up to 95% of the spring restoring force , thus generating low spring constant and low resonant frequency.

But not sufficient yet!

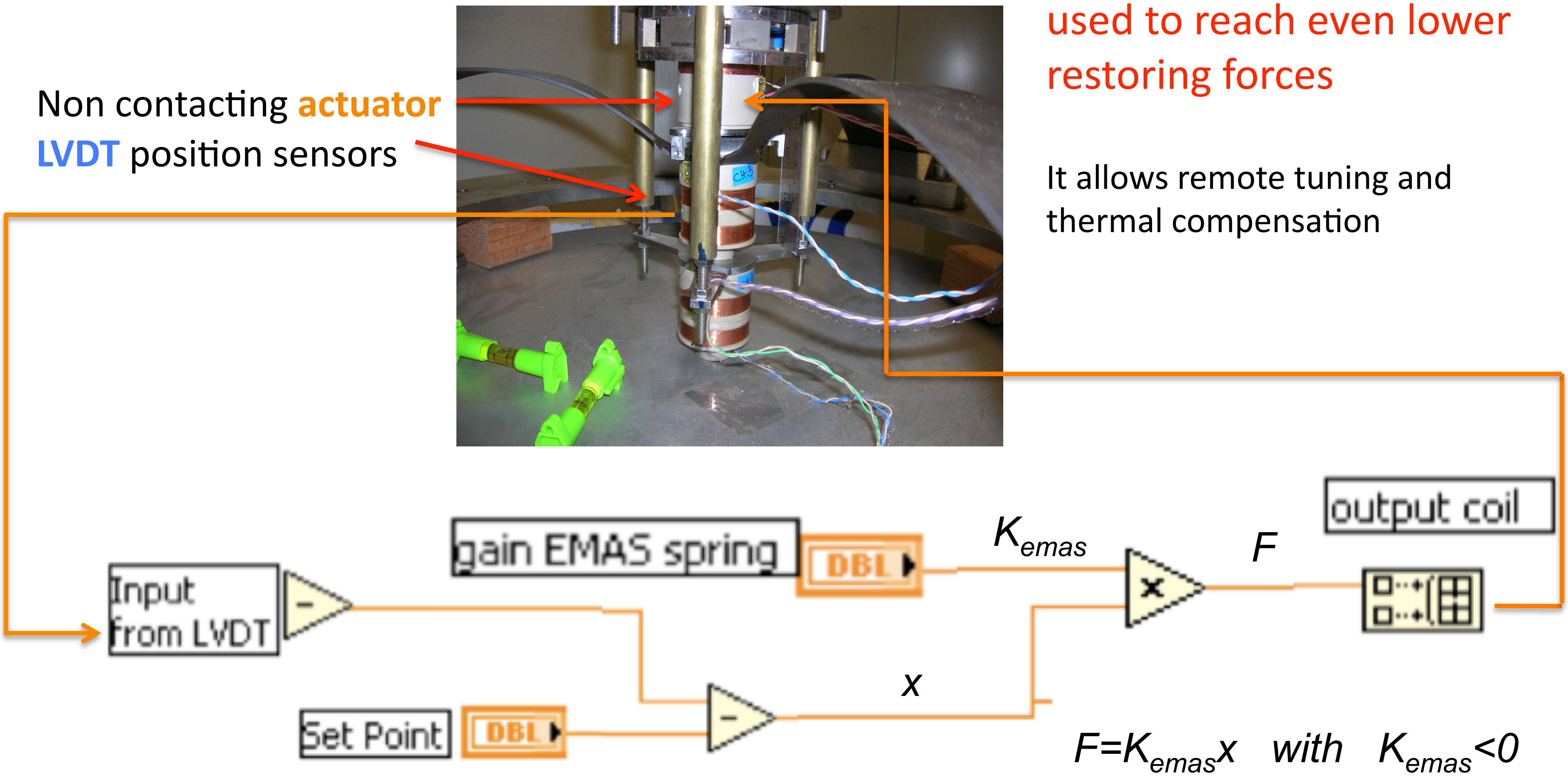
The ElectroMagnetic Anti Spring (EMAS) mechanism

The EMAS mechanism is used to reach even lower restoring forces

It allows remote tuning and thermal compensation

Non contacting **actuator**

LVDT position sensors

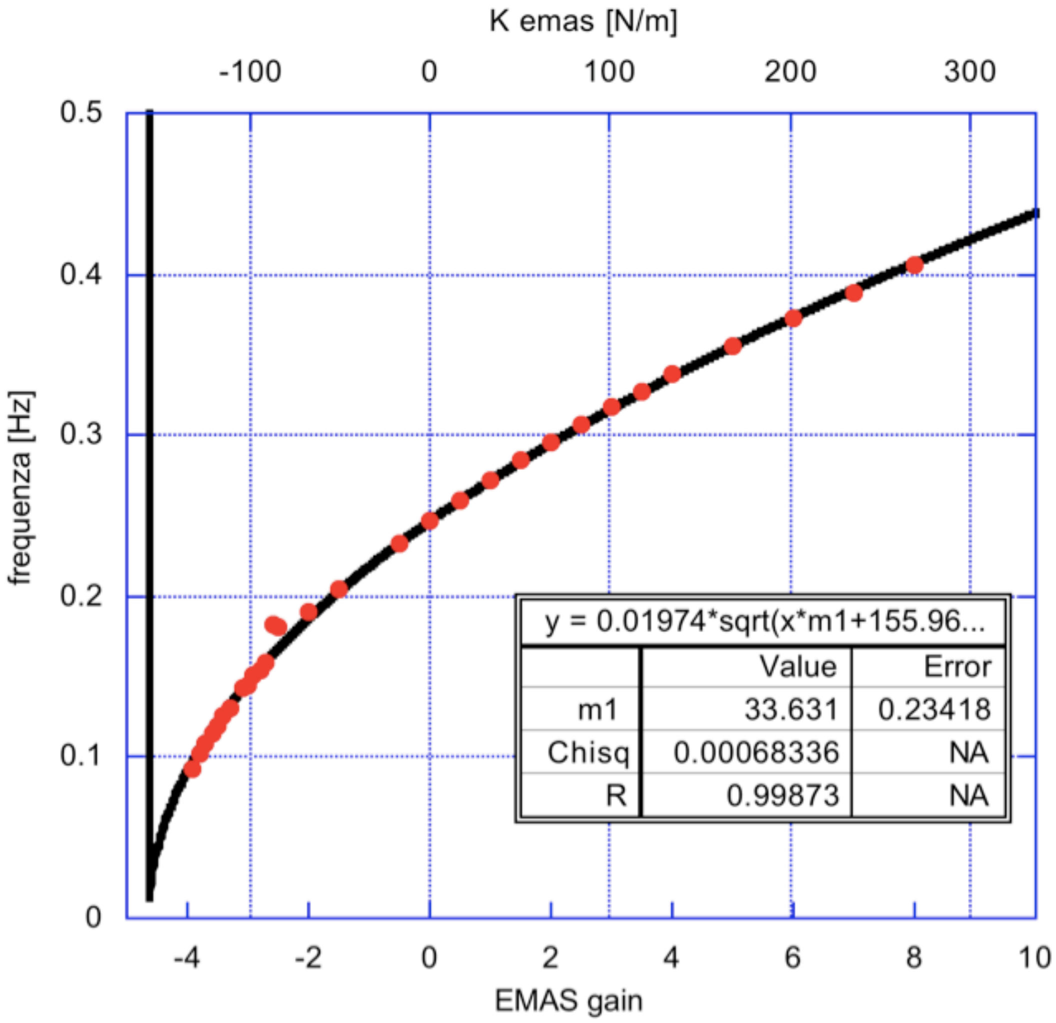


$F=K_{emas}x$ with $K_{emas}<0$

M. Mantovani, R. DeSalvo, *One Hertz Seismic Attenuation for Low Frequency Gravitational Waves Interferometers*, accepted for publication on Nucl. Instr. and Meth. (2005).

How well GAS and EMAS work

- Filter’s resonan
  frequency
  tuning

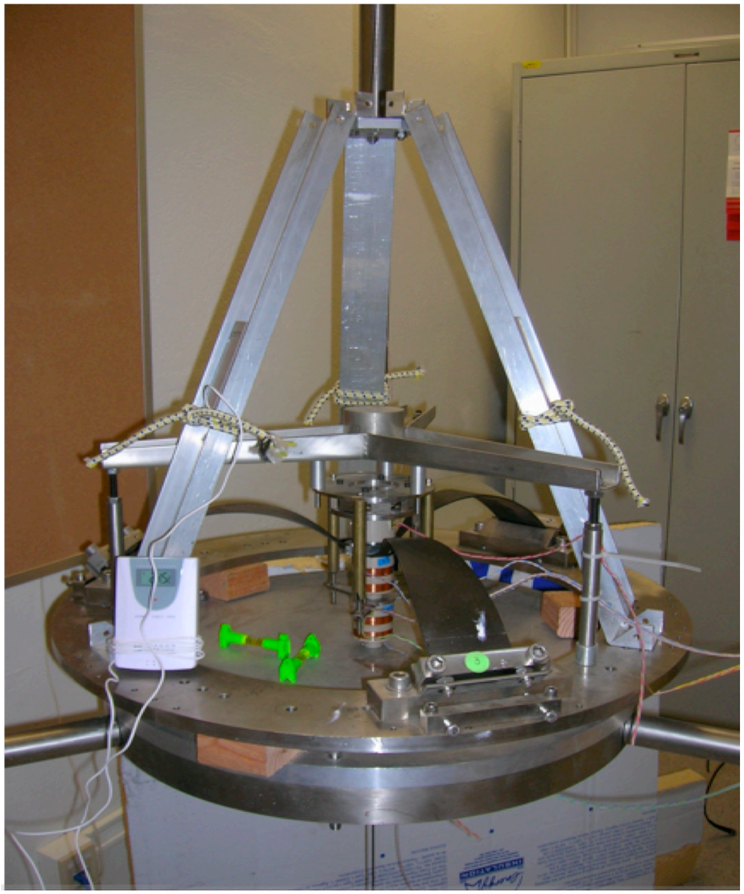


y = 0.01974*sqrt(x*m1+155.96...

	Value	Error
m1	33.631	0.23418
Chisq	0.00068336	NA
R	0.99873	NA

Experimental setup

- THE GAS-EMAS filter
- A “microscope” for mesoscale effects



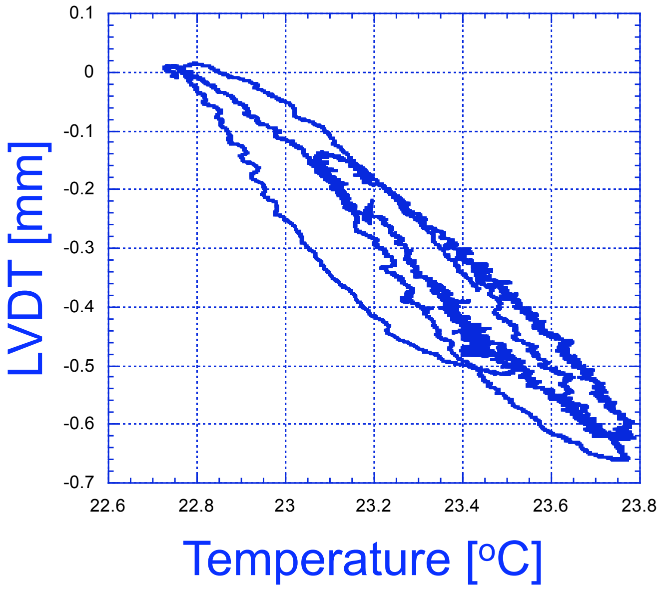
- the arbitrarily low resonant frequency from the Anti-Spring effects (GAS and EMAS) allow the exploration of Hysteresis, Thermal effects, Self Organized Criticality , and other underlying effects.

Observed problems in Mechanical oscillators

- Inconsistencies in Inverted Pendula and Geometric Anti Spring filters
- Hysteresis, Random walk of equilibrium point, even sudden Instability
- Manifested only at lower frequency

Evidence of hysteresis without actual movement in the thermal feedback

- Overnight lab thermal variations
- No feedback
- Thermal hysteresis of equilibrium point

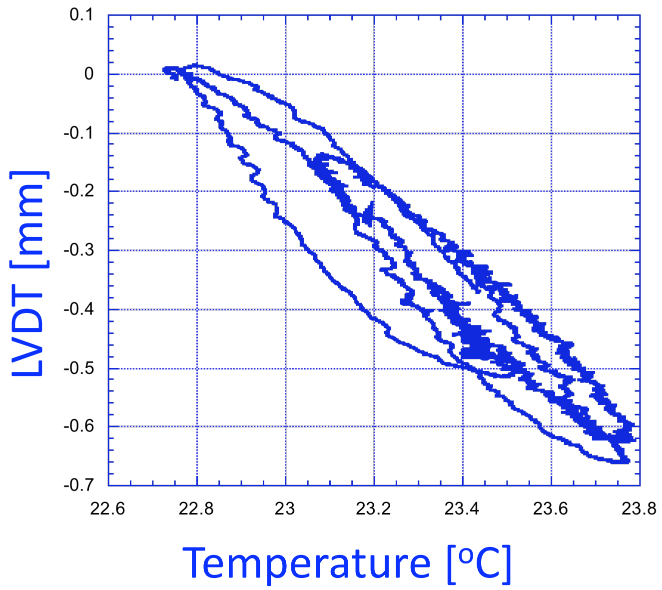


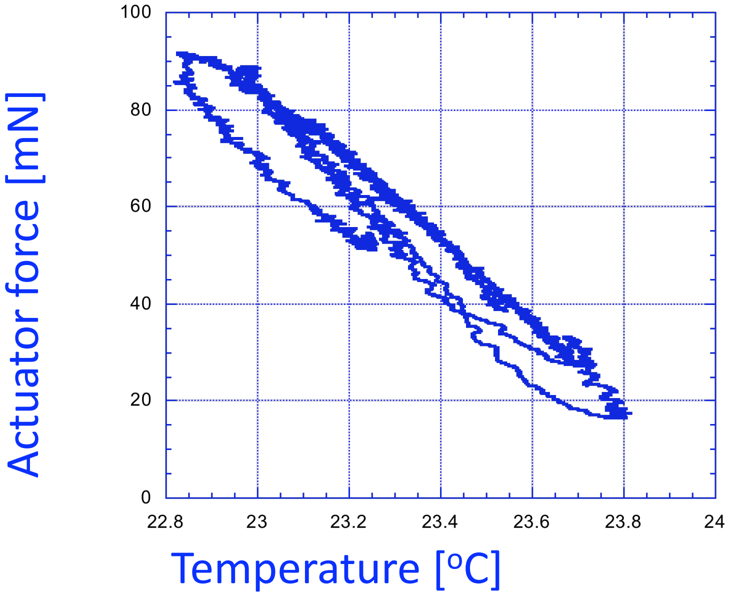
We tried to impeding hysteresis
By impeding movement

Hysteresis without actual movement ! !

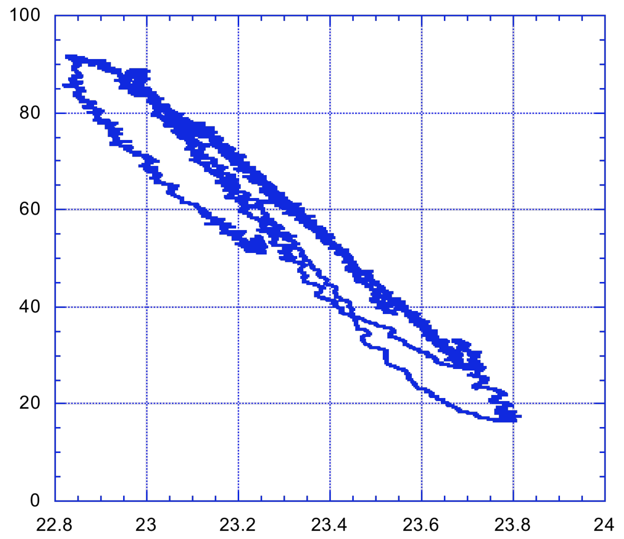
- Overnight lab thermal variations
- No feedback, free movement
- Thermal hysteresis of equilibrium point

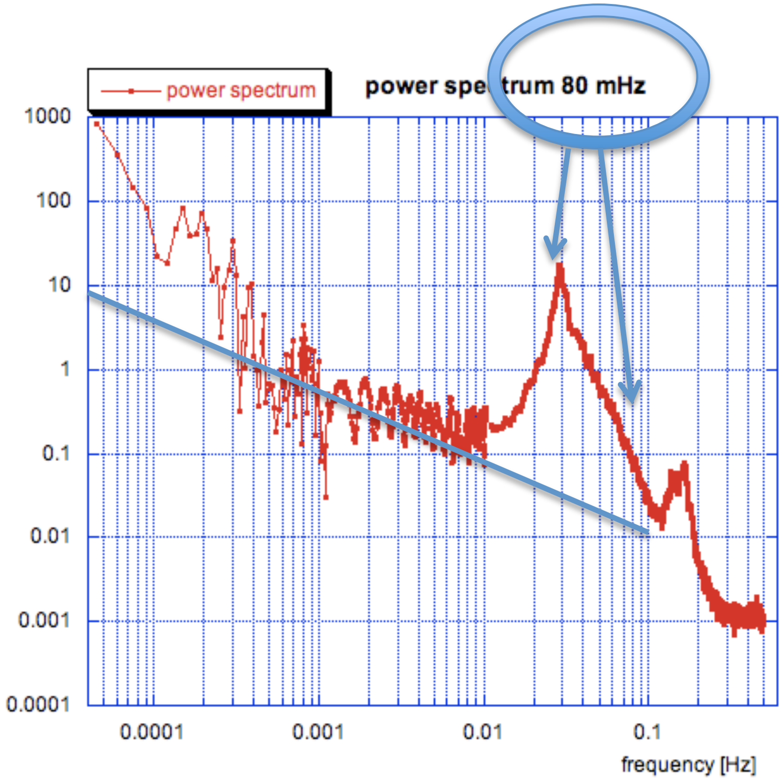
- Position feedback on
- No actual movement, expect no hysteresis
- Hysteresis shifts to the control current ! !





Hysteresis equal noise ! ! !





Hysteresis <u>does not</u> originate from the macroscopic movement **but from a microscopic stress dynamics** inside the material!

Hysteresis advanced by bumps ➔ 1/f noise

Instability at Low frequency

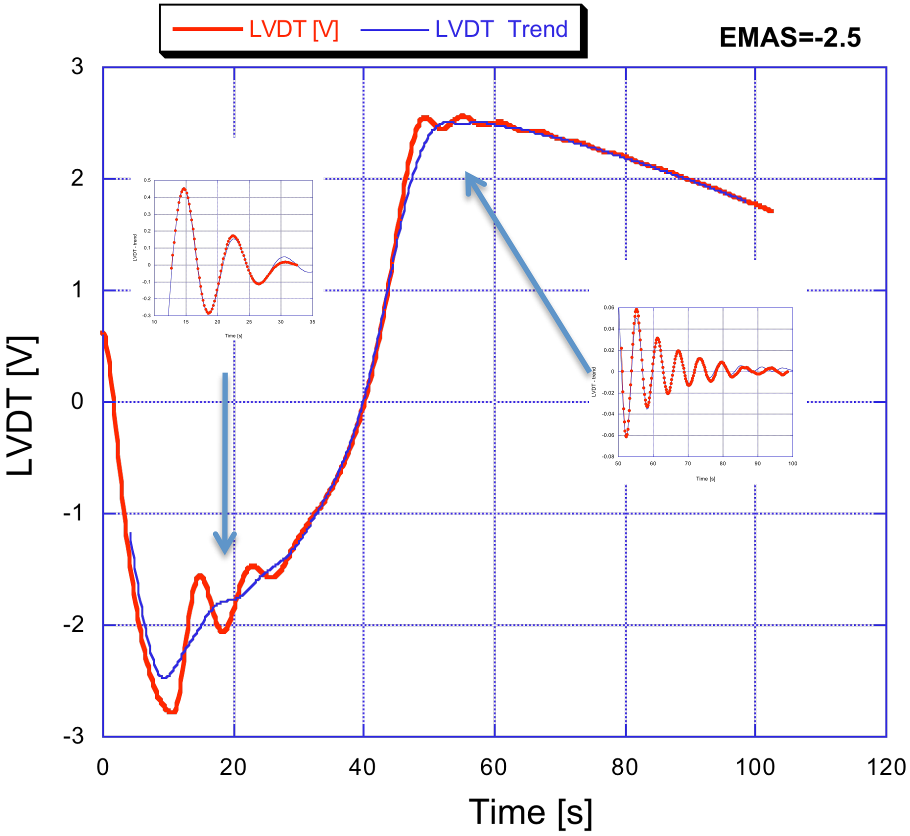
Low frequency instability

- As the system approaches lower and lower frequencies, sometimes it suddenly escapes from its equilibrium position in an un-predictable way

=> RUNS-OFF

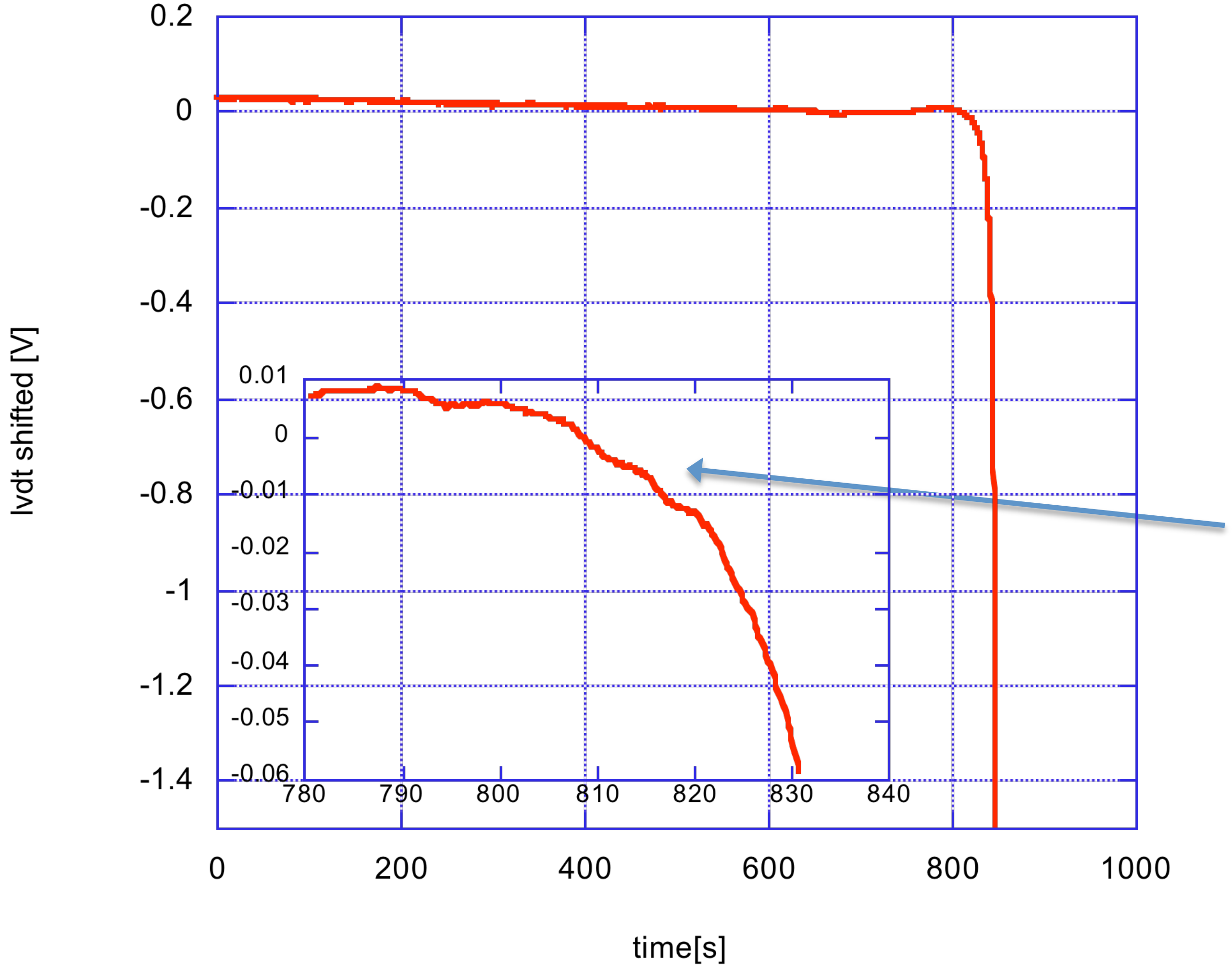
Example:

- excitation triggers a ringdown
- the spring spontaneously jumps to a new equilibrium point
- Oscillates around the new e.p.



Changing Young's modulus ➔ Instability

Some suddenly-activated mechanism occurs inside the blade



The filter abandons the equilibrium position slowly, then accelerates away

The time scale is of many seconds

The acceleration is "bumpy" due to individual avalanches

Avalanches propagate across the entire 38 cm blades

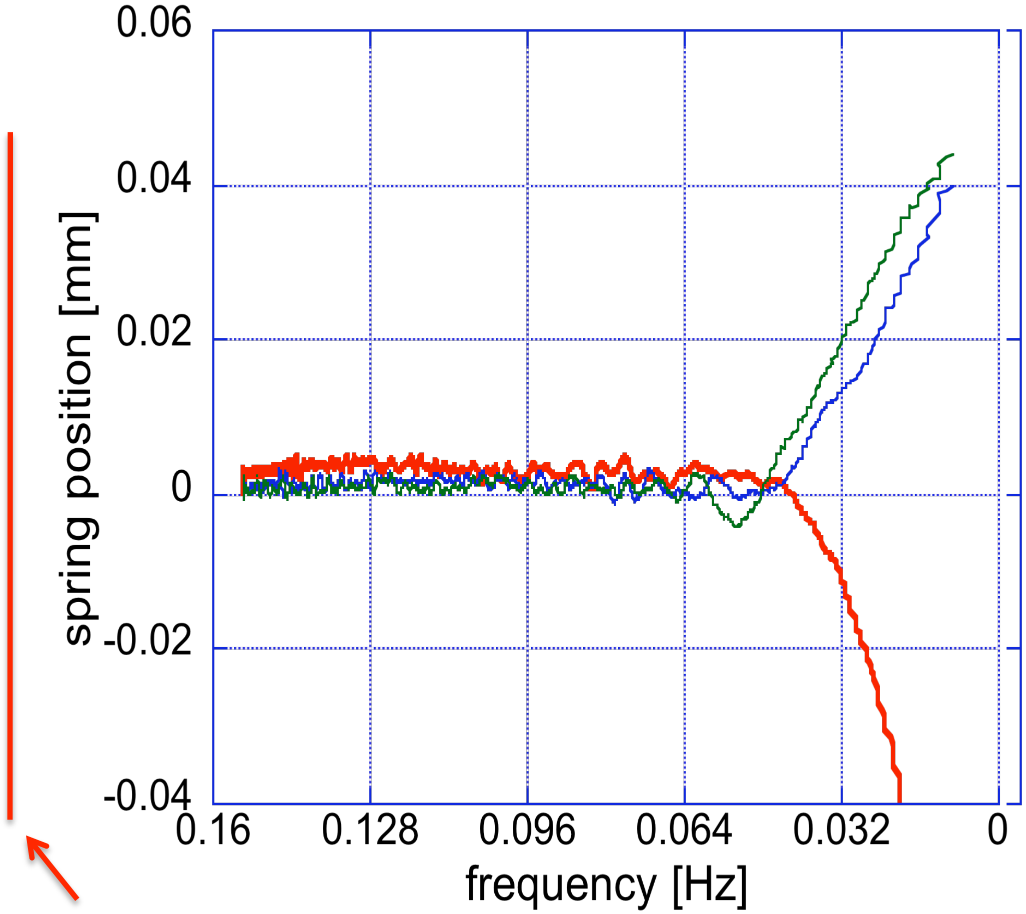
Low frequency instability

65 kg payload
can fall
indifferently up
or down

NO CREEP,

NO GRAVITY
DRIVEN EFFECT

It is the Young's
Modulus that
Suddenly fails!

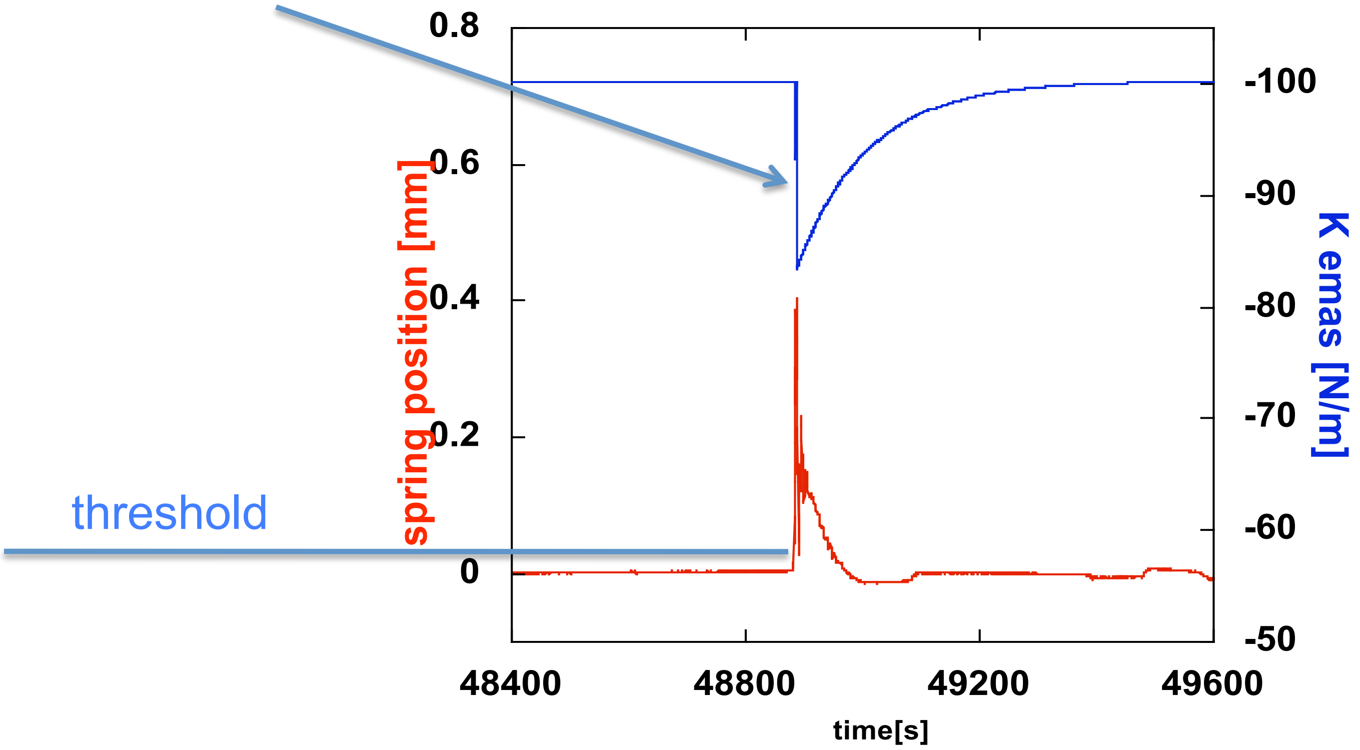


instability region mm
starting from ~ 0.2 Hz

The run-off can be controlled !

Control program detects the beginning of a run-off @ a threshold 30 mV=24mm

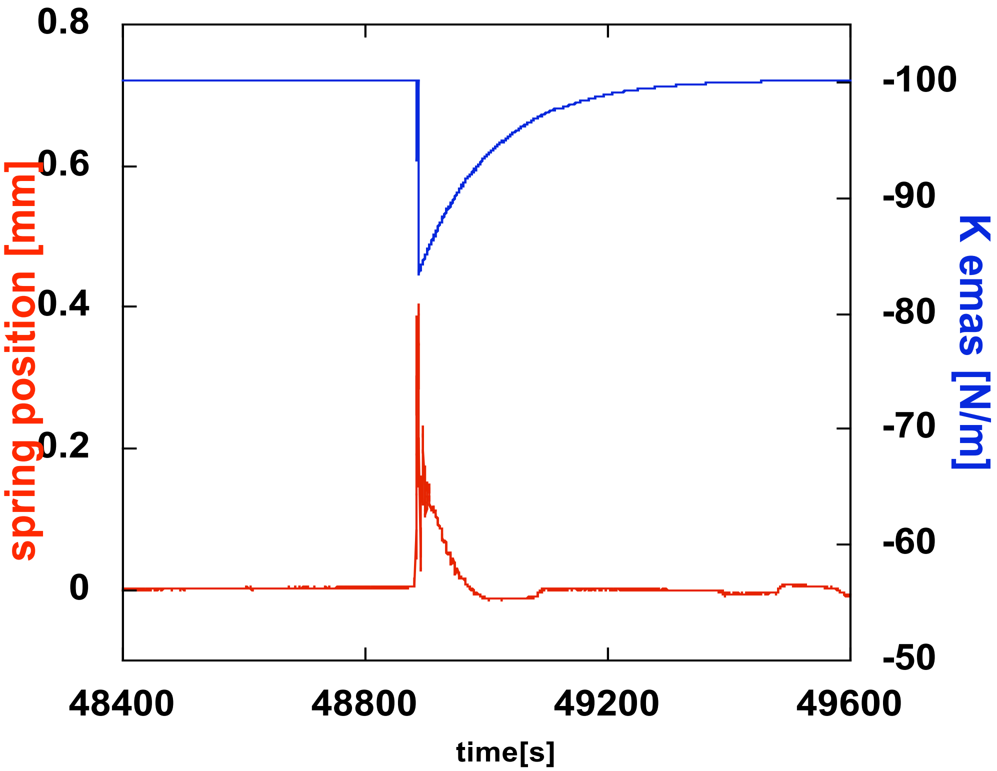
K_{emas} reduced toward less negative value, give more time for re-entanglement



The propagation of the avalanches across the blade is stopped

The system re-stabilizes at a different equilibrium position.

The feedback brings the spring back to the working point.



Explanation:

restoring force of the crystal lattice nulled by the GAS and EMAS mechanism,

System kept stable by the restoring force of entangled dislocations.

Perturbations cause some disentanglement, THE DOMINO EFFECT PROPAGATES AVALANCHES OVER THE WHOLE SPRING'S VOLUME,

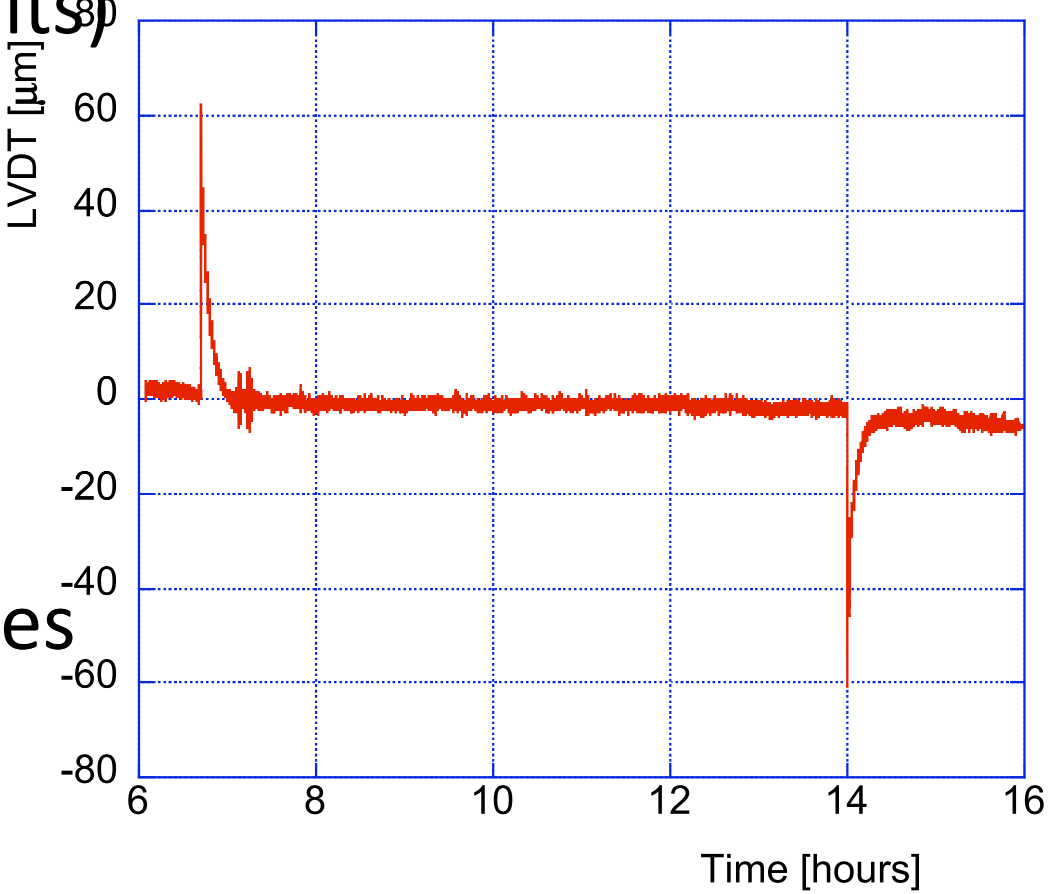
trigger collapse

reduced EMAS gain gives back control to crystal elasticity

stops the spreading

Run-off causes

- Thermal drifts
- Drifting forces (tilts)
- External jerks

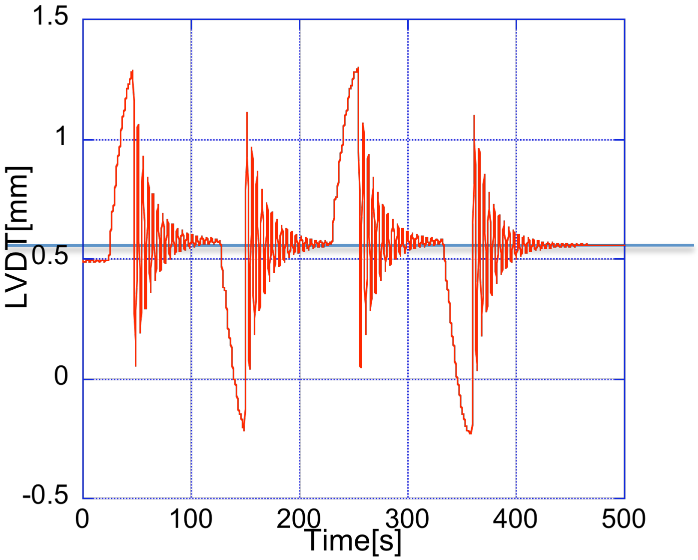


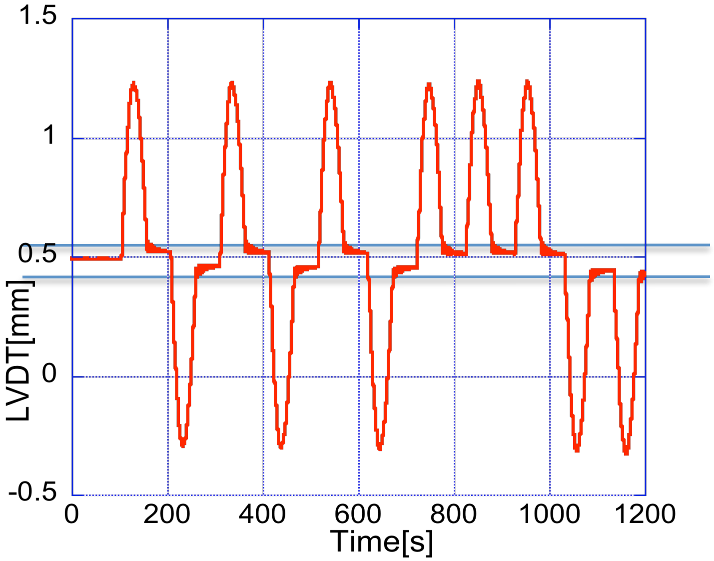
- No external causes
- No run-offs

Hysteresis and anelasticity

Exploring the effects of hysteresis at various frequencies

frequency 0.21 Hz (>0.2Hz) 113 N/m





We apply a force lifting the spring to a certain height, then cut the force and let the system oscillate freely:

NO HYSTERESIS OBSERVED

OSCILLATIONS APPEAR TO WASH-OUT HYSTERESIS

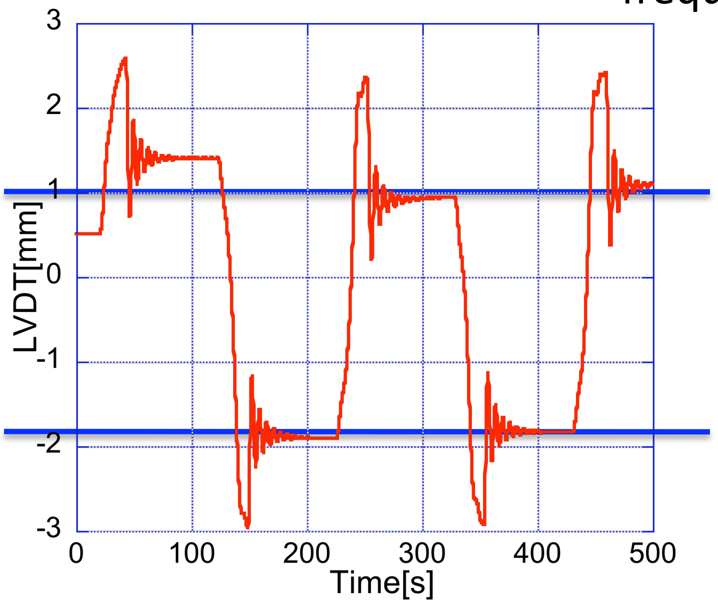
Subjecting the system to the same force, but slowly returning the lifting force to zero, thus generating no oscillations:

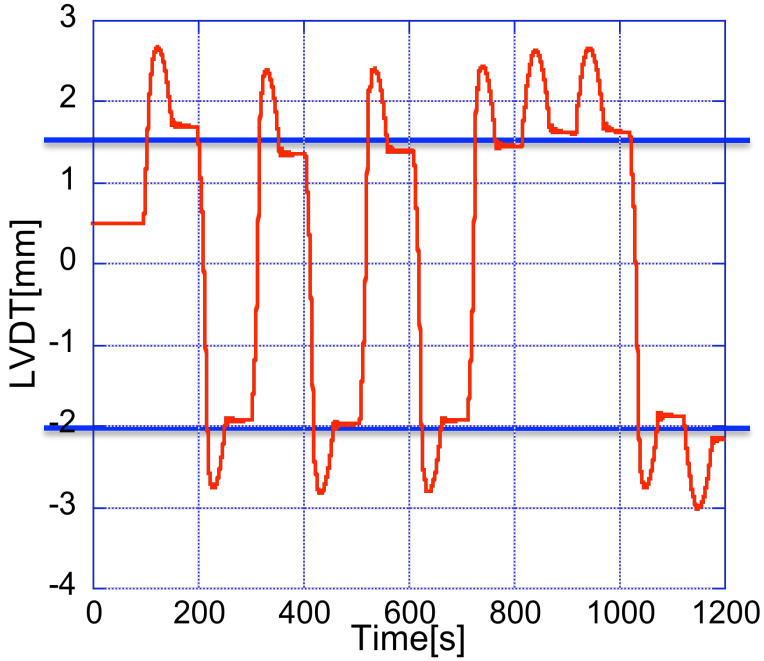
HYSTERESIS OBSERVED FOR ALTERNATE SIGN EXCITATION

NO HYSTERESIS FOR SAME SIGN EXCITATION

Hysteresis grows much larger at lower frequency

frequency 0.15 Hz (<0.2Hz) 58 N/m

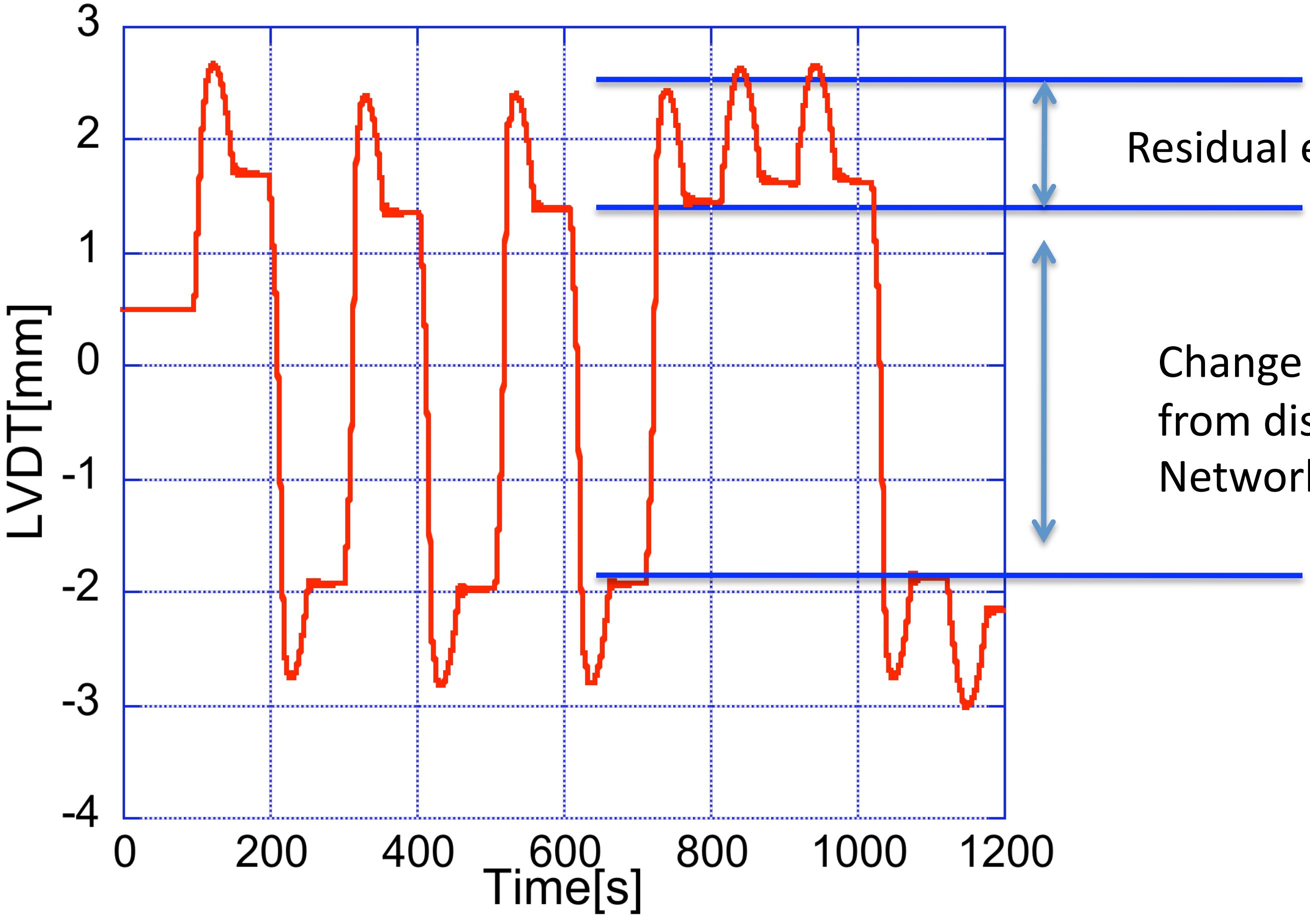




OSCILLATIONS APPEAR to be ineffective TO WASH-OUT HYSTERESIS at low frequency: not enough oscillations to delete hysteresis

Proposed explanation:
below 0.2 Hz the restoring force is dominated by entangled dislocations.
Under pulsed stresses dislocations mobilize and eventually re-entangle elsewhere generating a different equilibrium position.

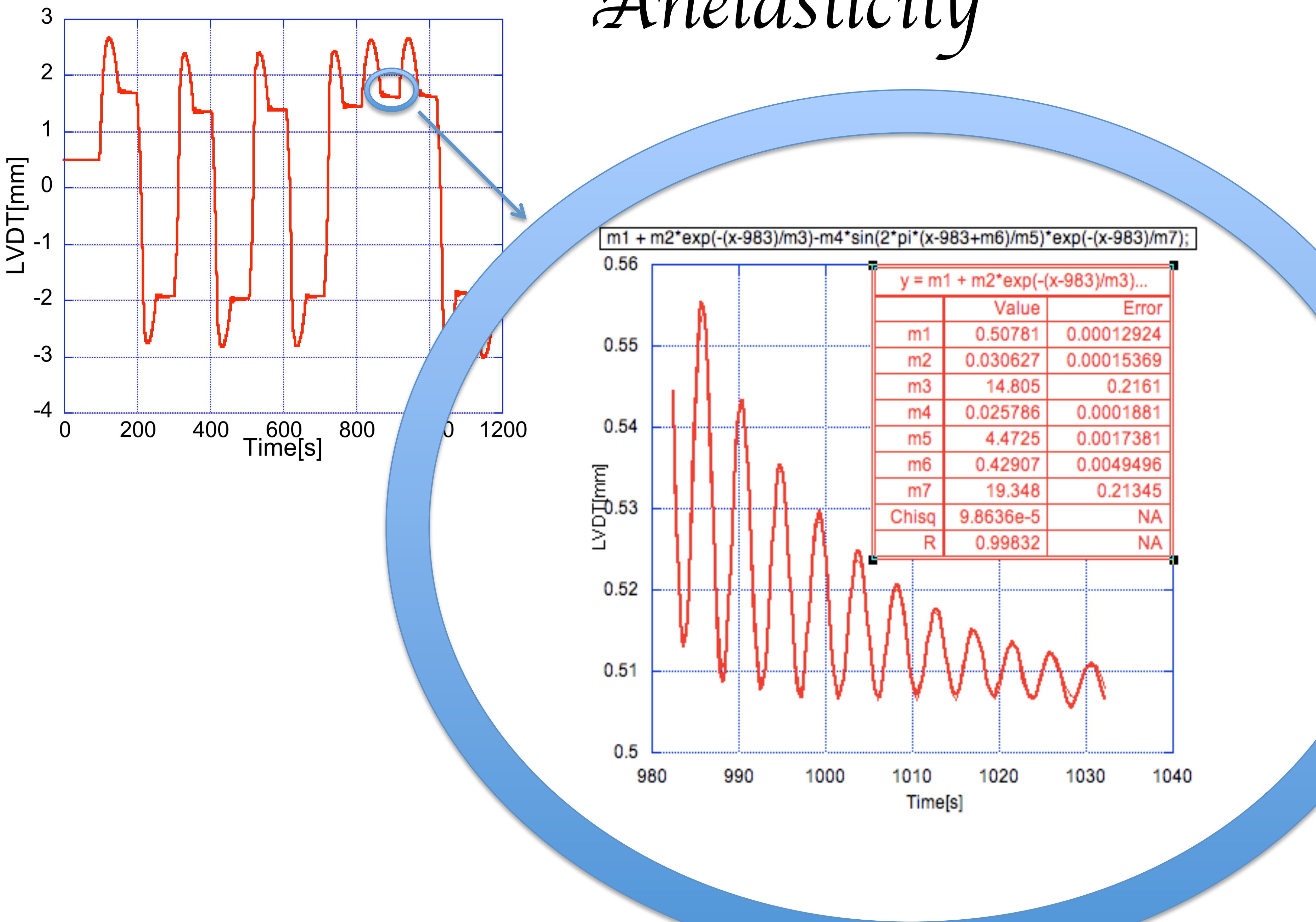
Hysteresis grows much larger at lower frequency



Residual elasticity from crystal

Change of equilibrium point
from disentangled, re-entangled
Network of dislocations

Anelasticity



m1 + m2*exp(-(x-983)/m3)-m4*sin(2*pi*(x-983+m6)/m5)*exp(-(x-983)/m7);

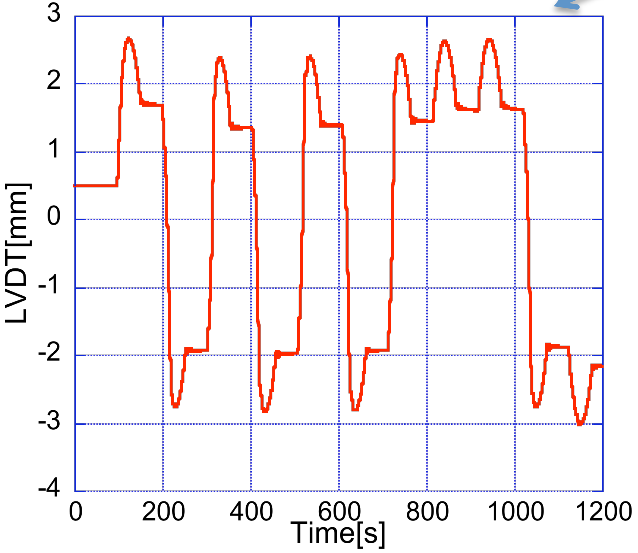
y = m1 + m2*exp(-(x-983)/m3)...

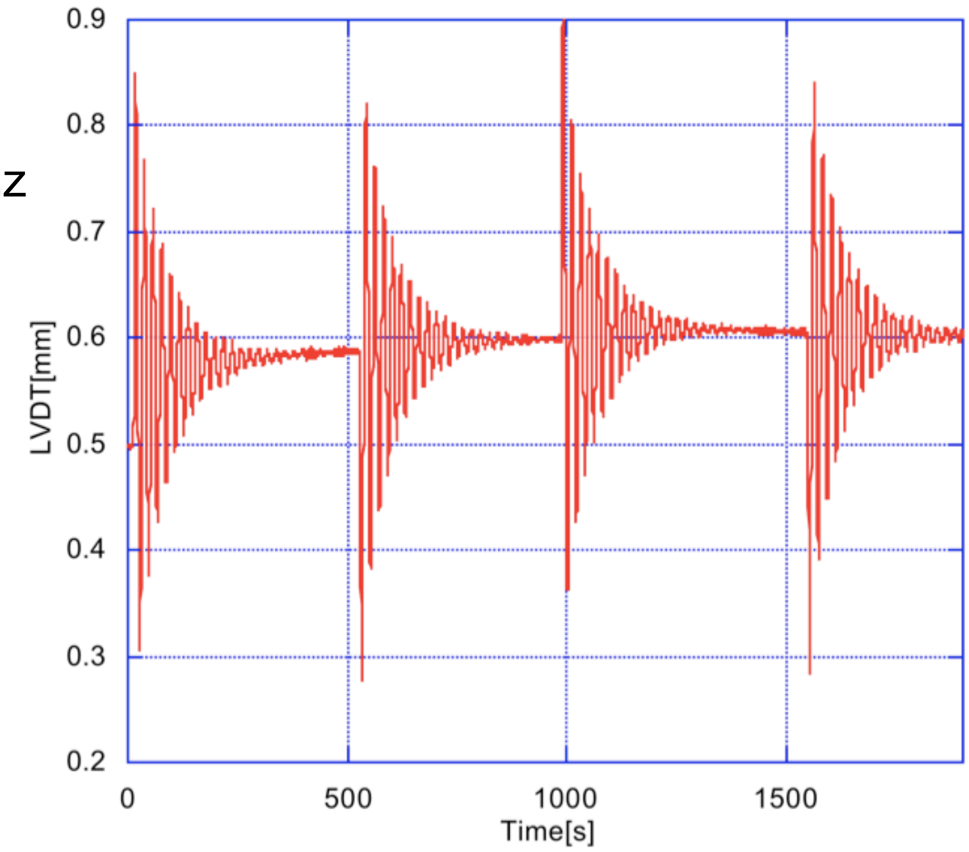
	Value	Error
m1	0.50781	0.00012924
m2	0.030627	0.00015369
m3	14.805	0.2161
m4	0.025786	0.0001881
m5	4.4725	0.0017381
m6	0.42907	0.0049496
m7	19.348	0.21345
Chisq	9.8636e-5	NA
R	0.99832	NA

Controlling hysteresis

- Forced, slowly decaying oscillations eliminate hysteresis even at low frequency tune

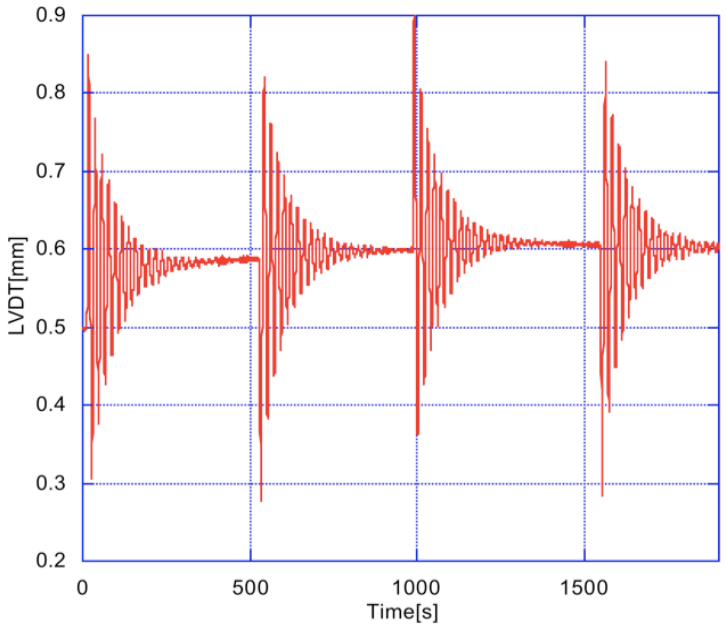
Same tune 0.15 Hz





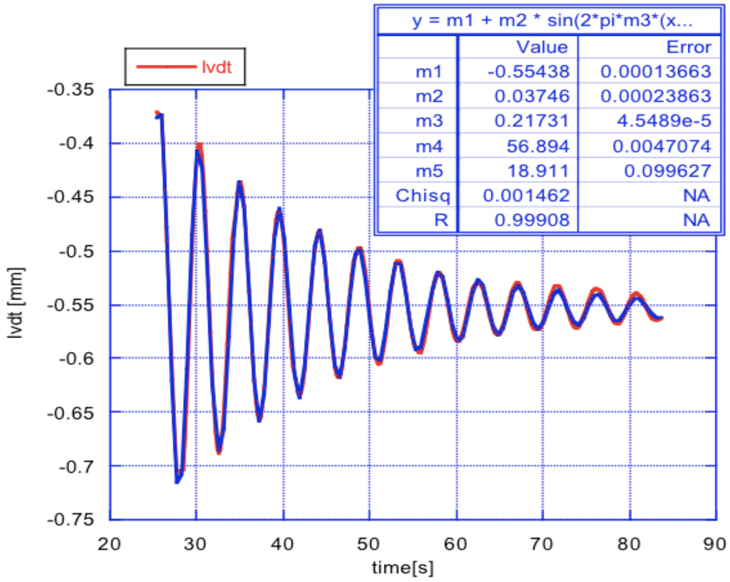
Controlling hysteresis ⇔ controlling noise

- Forced oscillations smooth out disloaction landscape
- Bring the system away from the critical slope
- Eliminate the source of avalanching

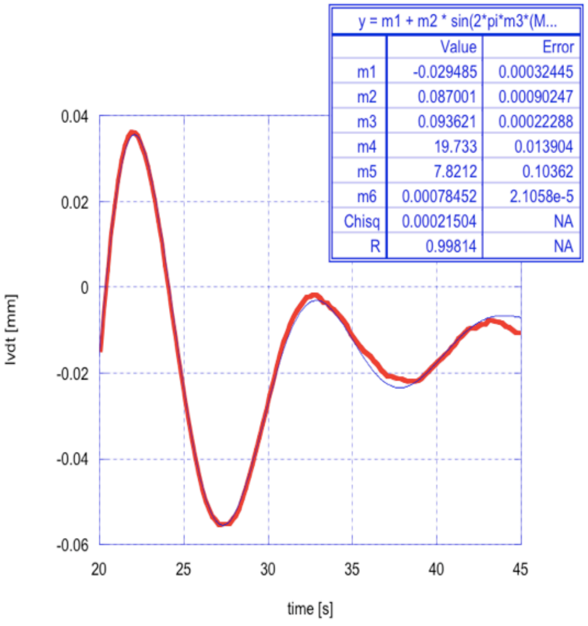


Quality factor measurements

Quality factor measurement

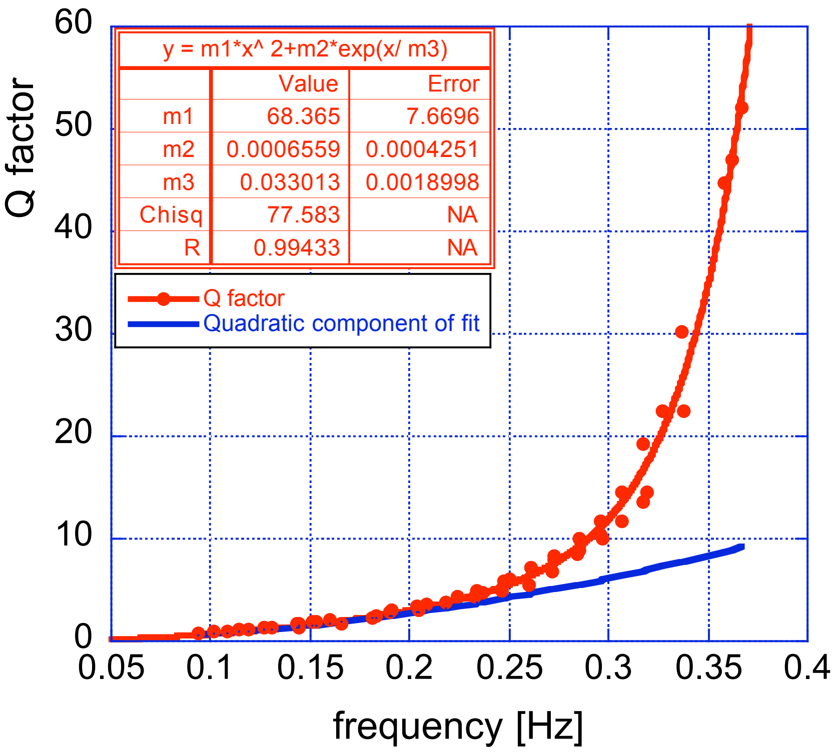


y = m1 + m2 * sin(2*pi*m3*(x...		
	Value	Error
m1	-0.55438	0.00013663
m2	0.03746	0.00023863
m3	0.21731	4.5489e-5
m4	56.894	0.0047074
m5	18.911	0.099627
Chisq	0.001462	NA
R	0.99908	NA



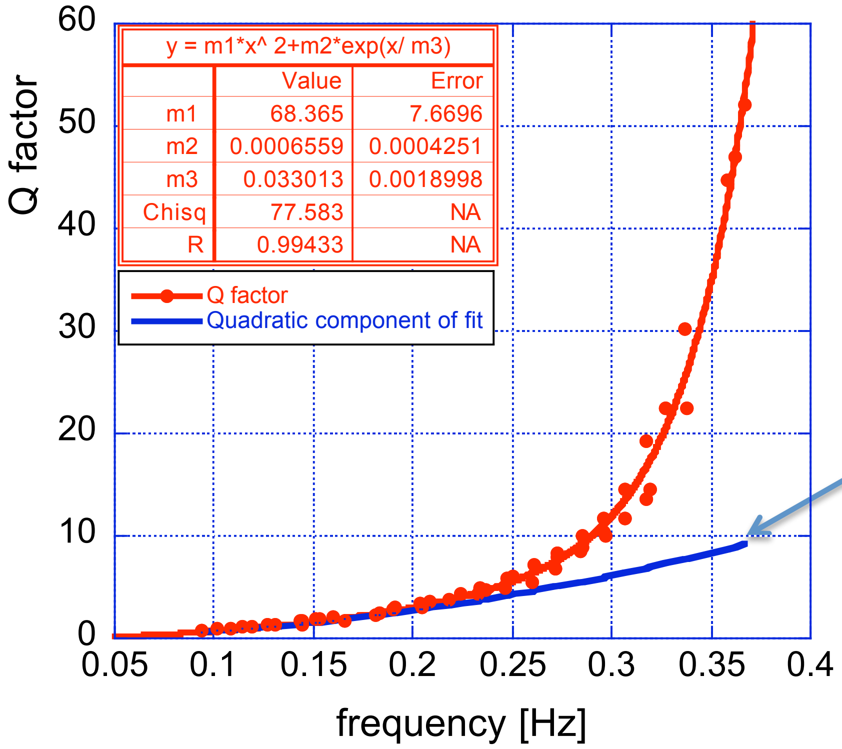
y = m1 + m2 * sin(2*pi*m3*(M...		
	Value	Error
m1	-0.029485	0.00032445
m2	0.087001	0.00090247
m3	0.093621	0.00022288
m4	19.733	0.013904
m5	7.8212	0.10362
m6	0.00078452	2.1058e-5
Chisq	0.00021504	NA
R	0.99814	NA

- METHOD
- Change the frequency with GAS and EMAS mechanism
- Acquire ringdowns
- Measure Q = wt



y = m1*x^ 2+m2*exp(x/ m3)		
	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA

Quality factor measurement



y = m1*x^ 2+m2*exp(x/ m3)

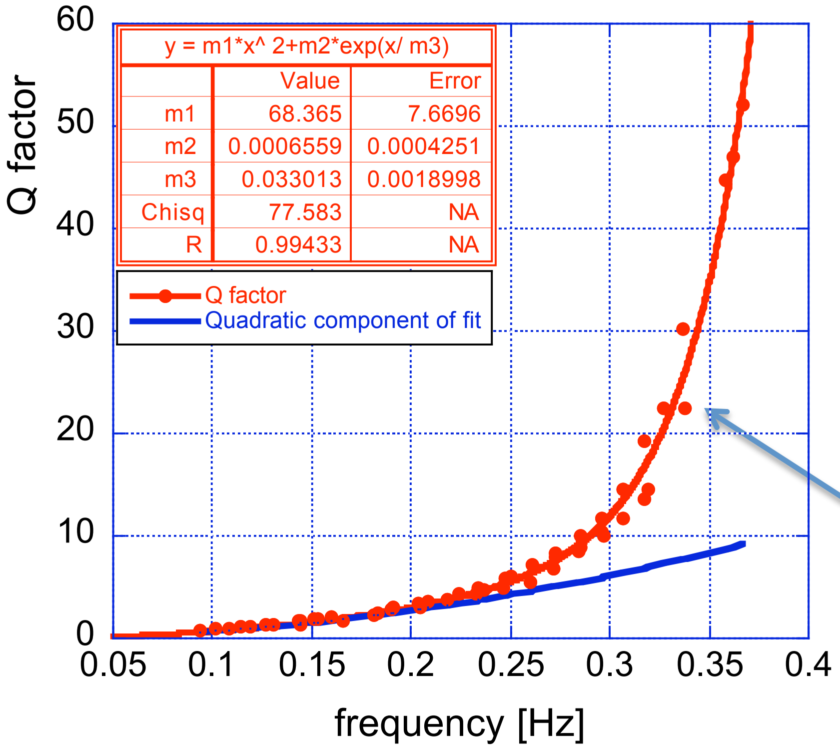
	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA

the expected behavior is quadratic

if the losses are frequency independent

Quality factor measurement

The fast increase of Q-factor implies reduced losses at higher frequencies



y = m1*x^ 2+m2*exp(x/ m3)

	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA

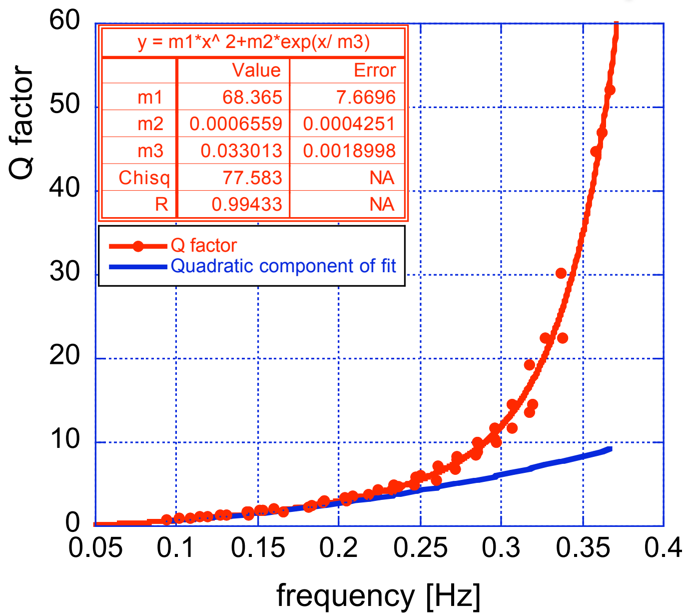
explainable if the dissipation process needs long time to develop:

AVALANCHES NEED LONG TIME TO DEVELOP

The deviation from quadratic was fit with an exponential function accounting for the exponential growth of avalanches with time

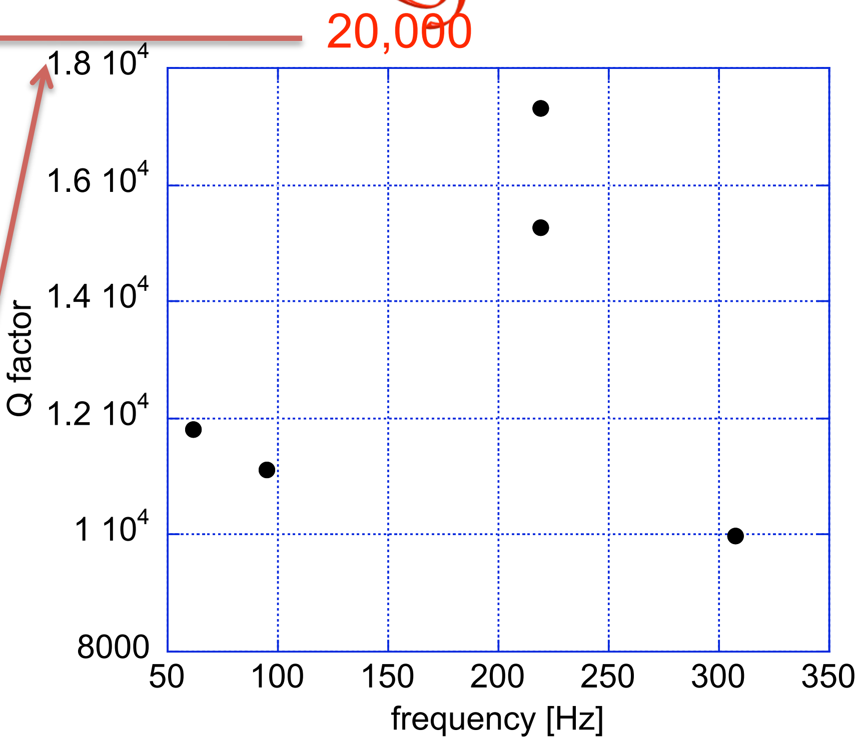
Maraging free blades Q-factor

- the exponential fit reaches the free blade Q-factor ($>10^4$) before 0.5 Hz ! ! ! .



y = m1*x^ 2+m2*exp(x/ m3)

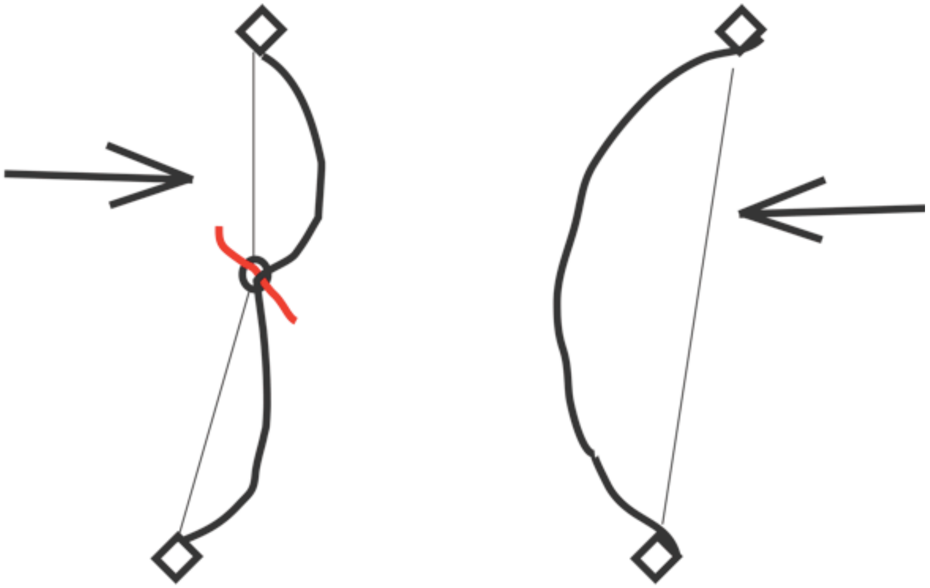
	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA



Fluctuating Young's modulus

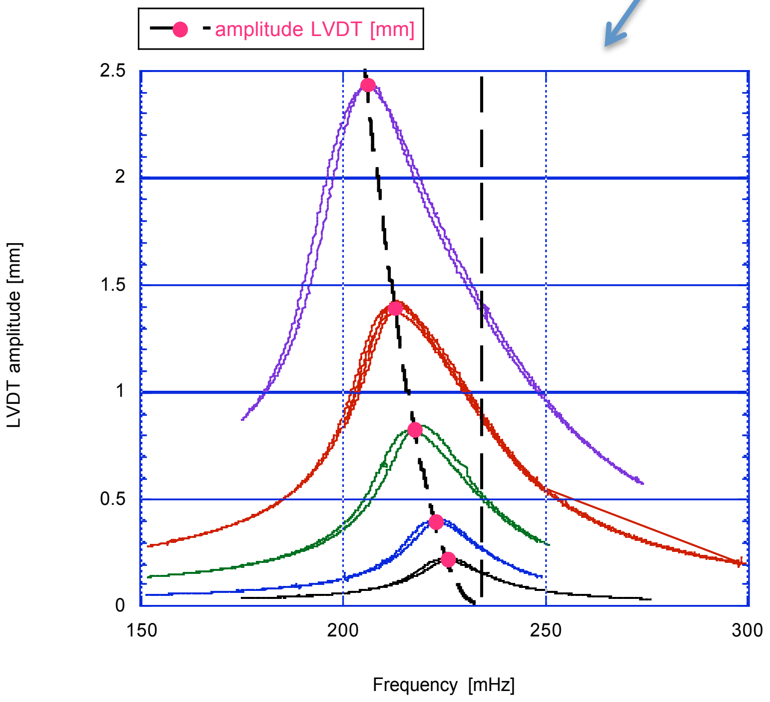
- Disentangling dislocations increase the dislocation free length
- Will increase the amount of modulus defect
- Will increase dissipation

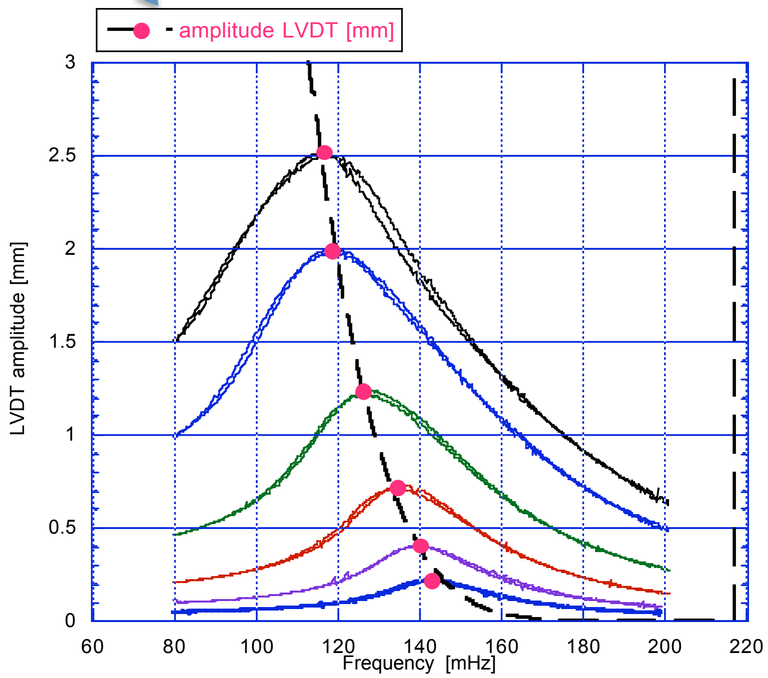
Forcing disentanglement with motion



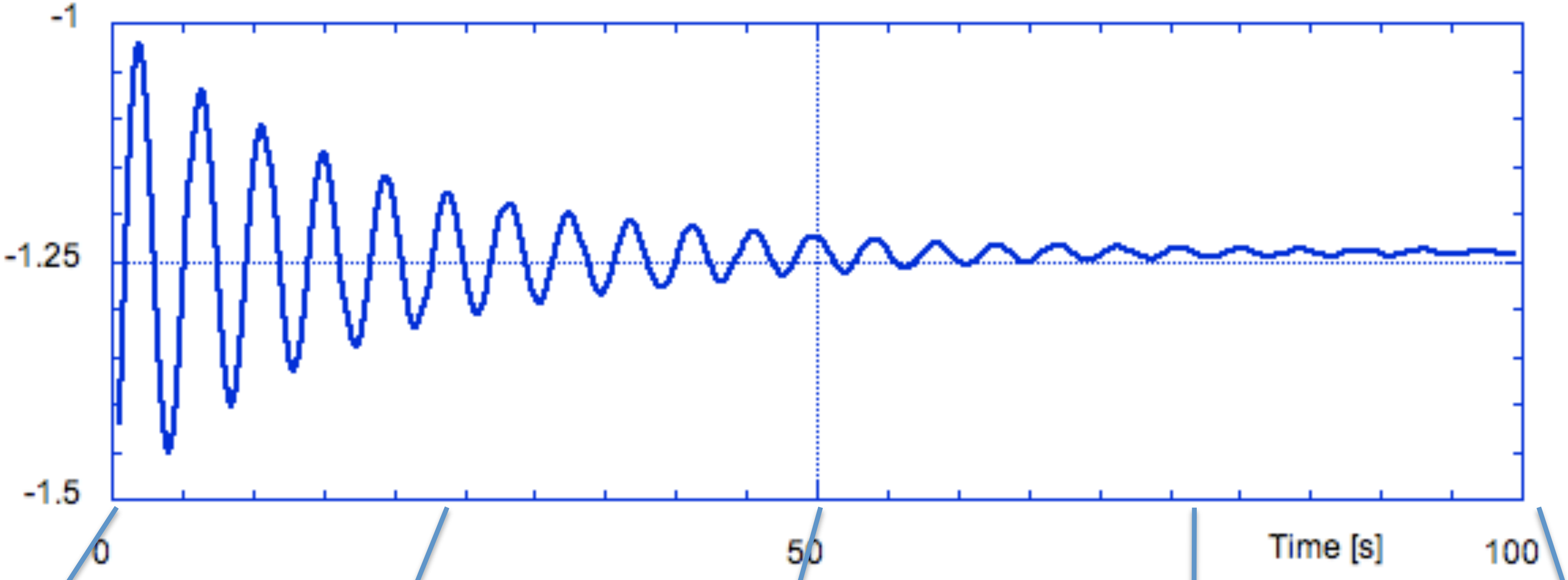
Frequency dependence from amplitude

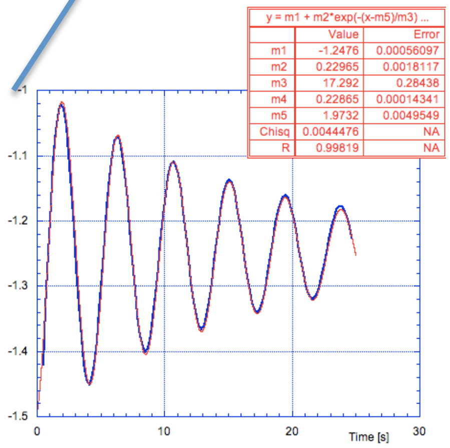
Swept sine excitation of different amplitudes.
Observed reduction of frequency for increasing excitation amplitude.
Experiment repeated for EMAS gain 0 and -2.



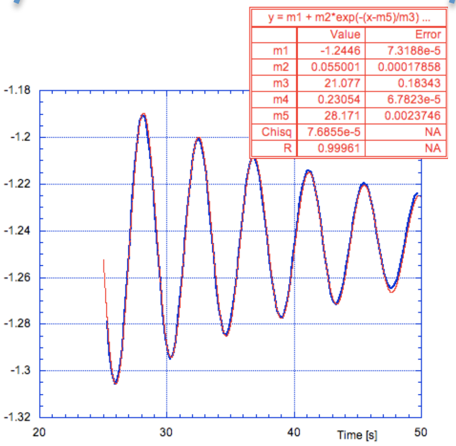


Ringdown analysis

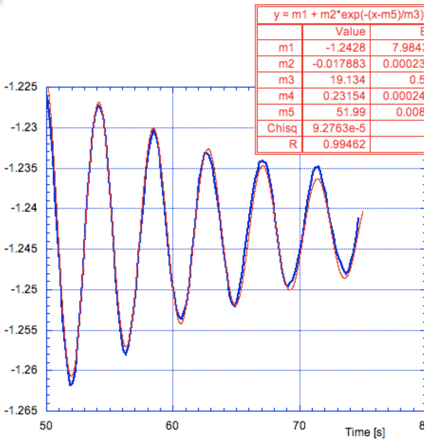




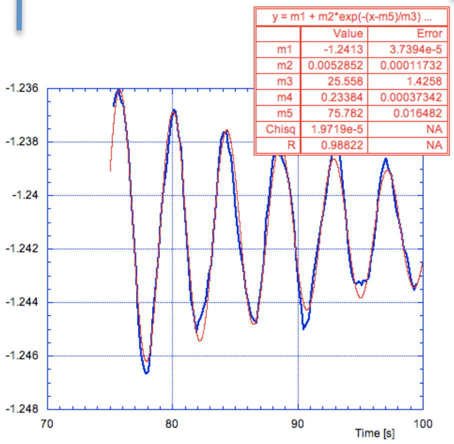
y = m1 + m2*exp(-(x-m5)/m3) ...		
	Value	Error
m1	-1.2476	0.00056097
m2	0.22965	0.0018117
m3	17.292	0.28438
m4	0.22865	0.00014341
m5	1.9732	0.0049549
Chisq	0.0044476	NA
R	0.99819	NA



y = m1 + m2*exp(-(x-m5)/m3) ...		
	Value	Error
m1	-1.2446	7.3188e-5
m2	0.055001	0.00017858
m3	21.077	0.18343
m4	0.23054	6.7823e-5
m5	28.171	0.0023746
Chisq	7.6855e-5	NA
R	0.99961	NA

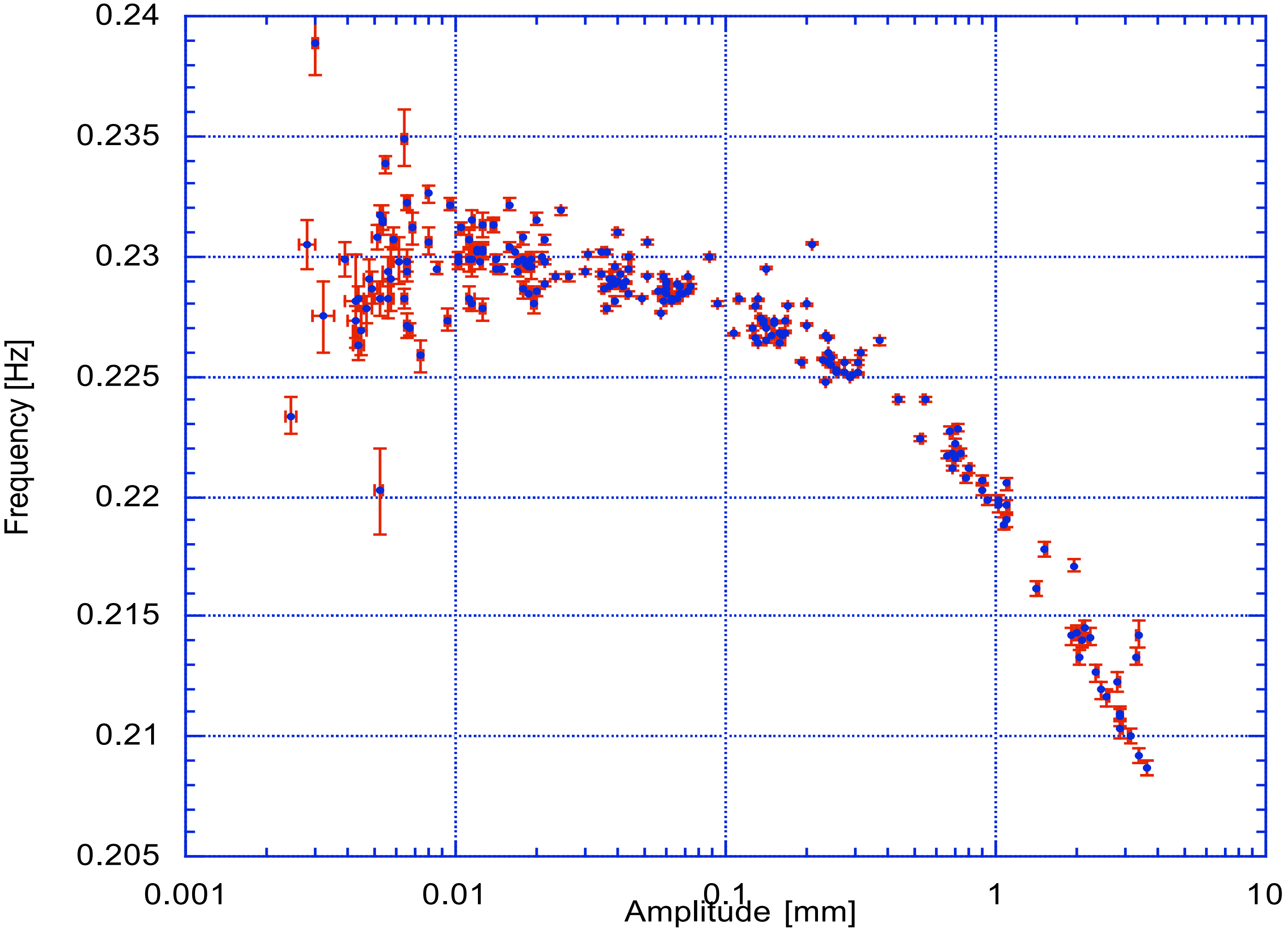


y = m1 + m2*exp(-(x-m5)/m3)		
	Value	E
m1	-1.2428	7.984
m2	-0.017883	0.00023
m3	19.134	0.5
m4	0.23154	0.00024
m5	51.99	0.008
Chisq	9.2763e-5	
R	0.99462	



y = m1 + m2*exp(-(x-m5)/m3) ...		
	Value	Error
m1	-1.2413	3.7394e-5
m2	0.0052852	0.00011732
m3	25.558	1.4258
m4	0.23384	0.00037342
m5	75.782	0.016482
Chisq	1.9719e-5	NA
R	0.98822	NA

Find similar behavior in the time domain by ring-down analysis.



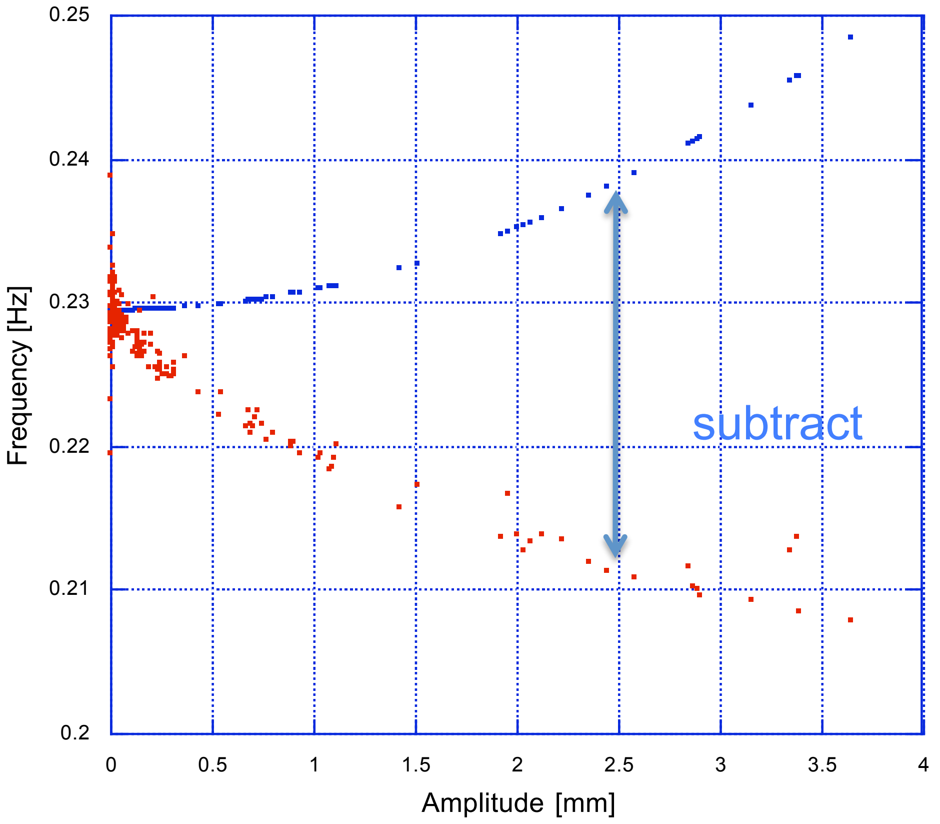
- We observe a frequency reduction at larger amplitudes…

- … while we expected the opposite!

Blue=expected

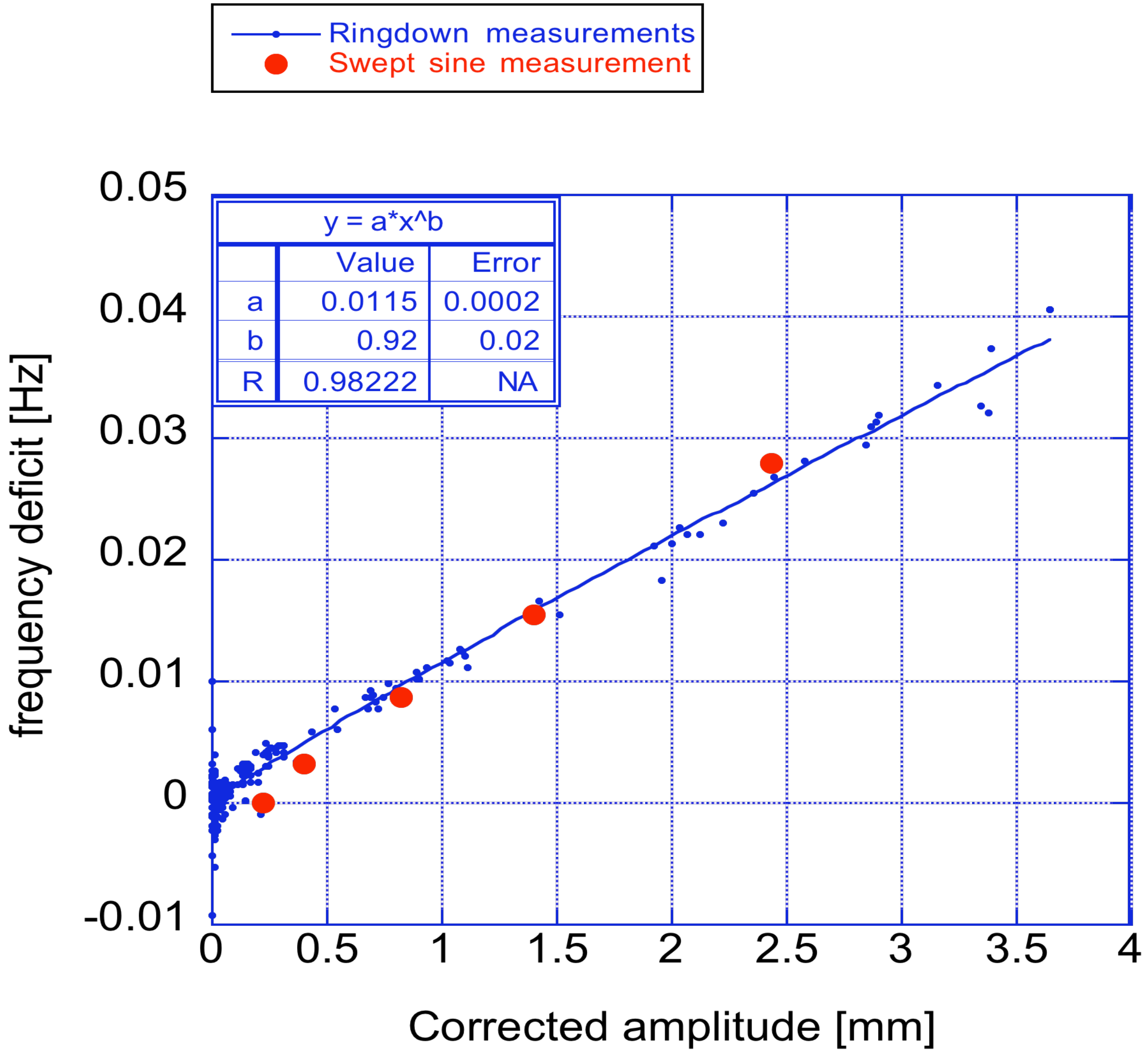
from measured GAS potential

Red=measured



Frequency deficit vs. oscillation amplitude

Young's modulus
Drops with
oscillation amplitude



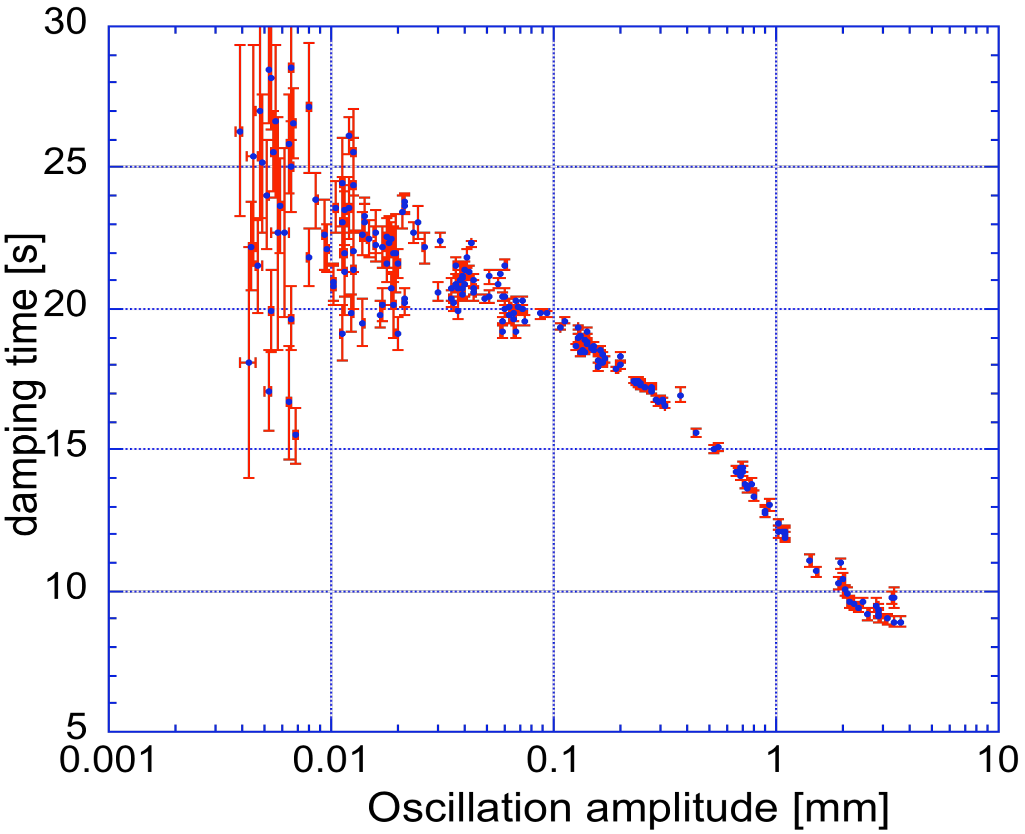
y = a*x^b

	Value	Error
a	0.0115	0.0002
b	0.92	0.02
R	0.98222	NA

Excess Dissipation at larger oscillation amplitude

Excess Dissipation at larger oscillation amplitude

- Analyzing ring-downs.



- damping time grows for smaller oscillation amplitude
- Proposed explanation: larger oscillations can disentangle more dislocations, which then move freely and cause increased dissipation and shorter damping times.

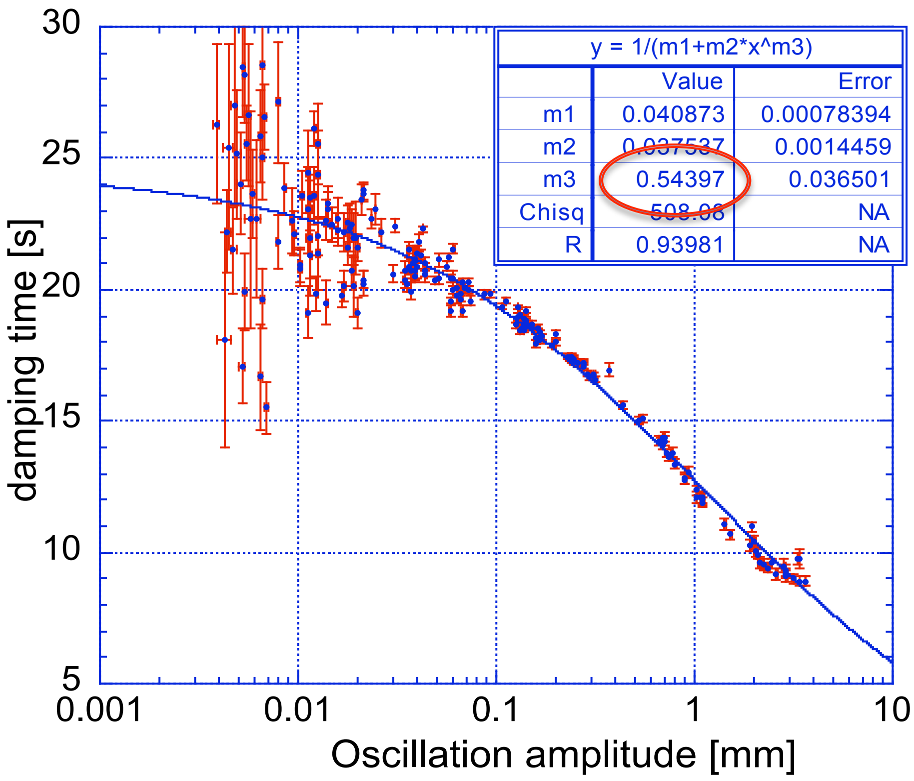
- Fitting the data with

$$\boxed{\tau = \frac{1}{d_0 + \delta A^y}}$$

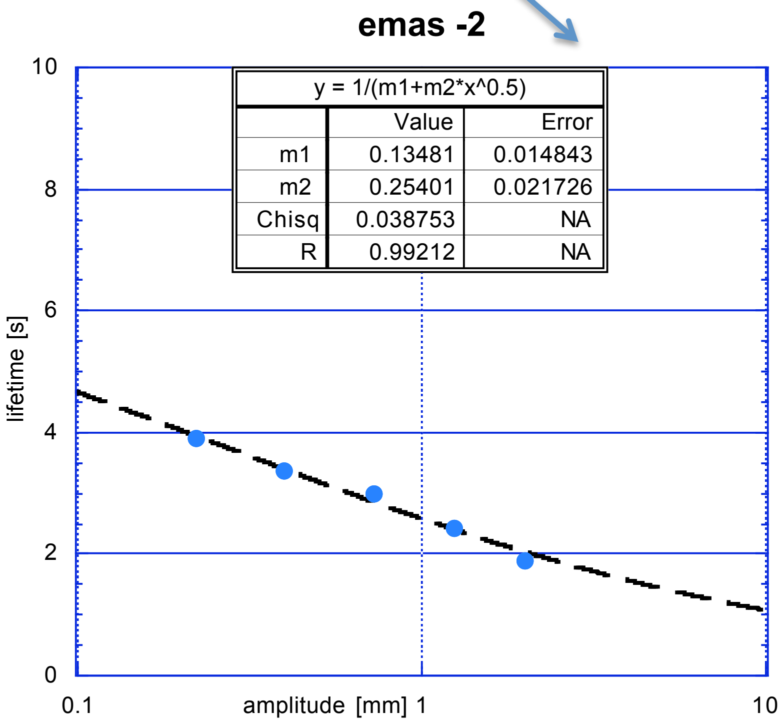
we found an amplitude exponent of ~ 0.5

power law => fractality / SOC ?

- Same behavior in the frequency domain



y = 1/(m1+m2*x^m3)	Value	Error
m1	0.040873	0.00078394
m2	0.037537	0.0014459
m3	0.54397	0.036501
Chisq	508.08	NA
R	0.93981	NA

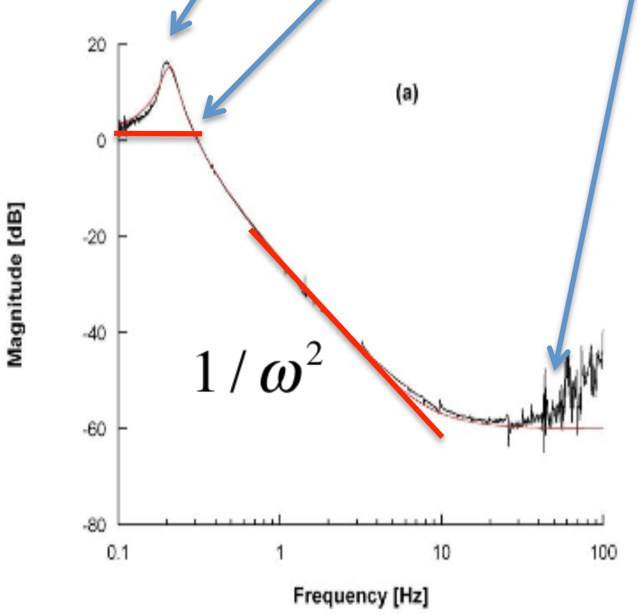


y = 1/(m1+m2*x^0.5)	Value	Error
m1	0.13481	0.014843
m2	0.25401	0.021726
Chisq	0.038753	NA
R	0.99212	NA

Anomalous
Transfer function of a GAS-filter

Transfer function of a GAS-filter

$$H_z(\omega) = \frac{\omega_o^2(1+i\phi)+\beta\omega^2}{\omega_o^2(1+i\phi)+i\gamma\omega-\omega^2}$$

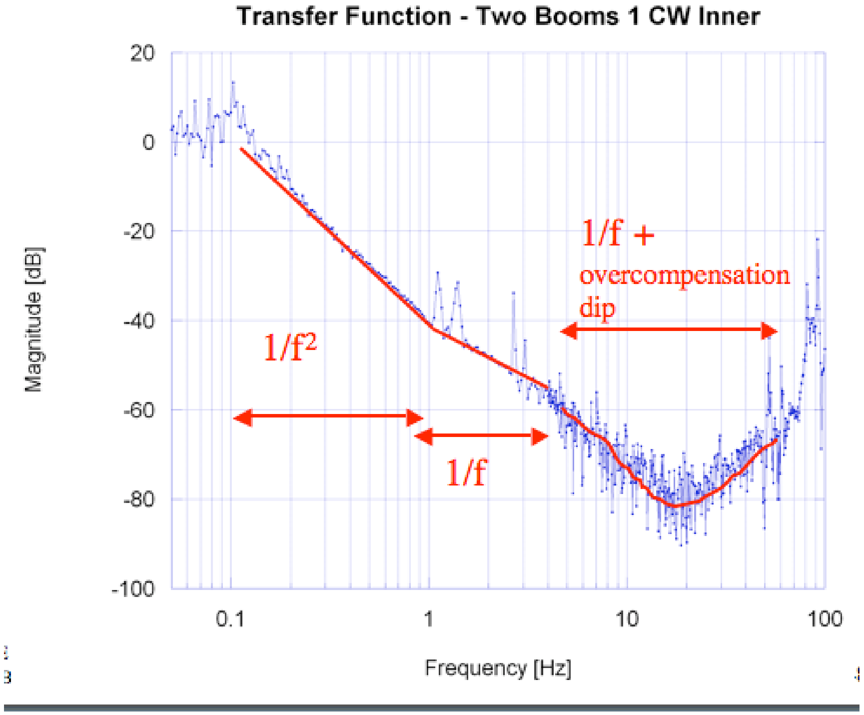


Fractal dynamics predicts 1/f noise

Experimentally found

Stationary and Unexpected 1/f

Transfer Function has been found when the GAS filter was tuned at or below 100 mHz



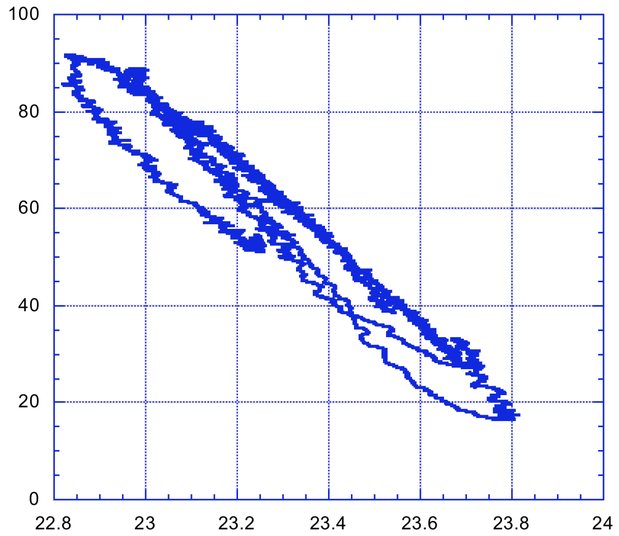
The SAS seismic attenuation system for the Advanced LIGO Gravitational Wave Interferometric Detectors. A.Stochino et al., 2008

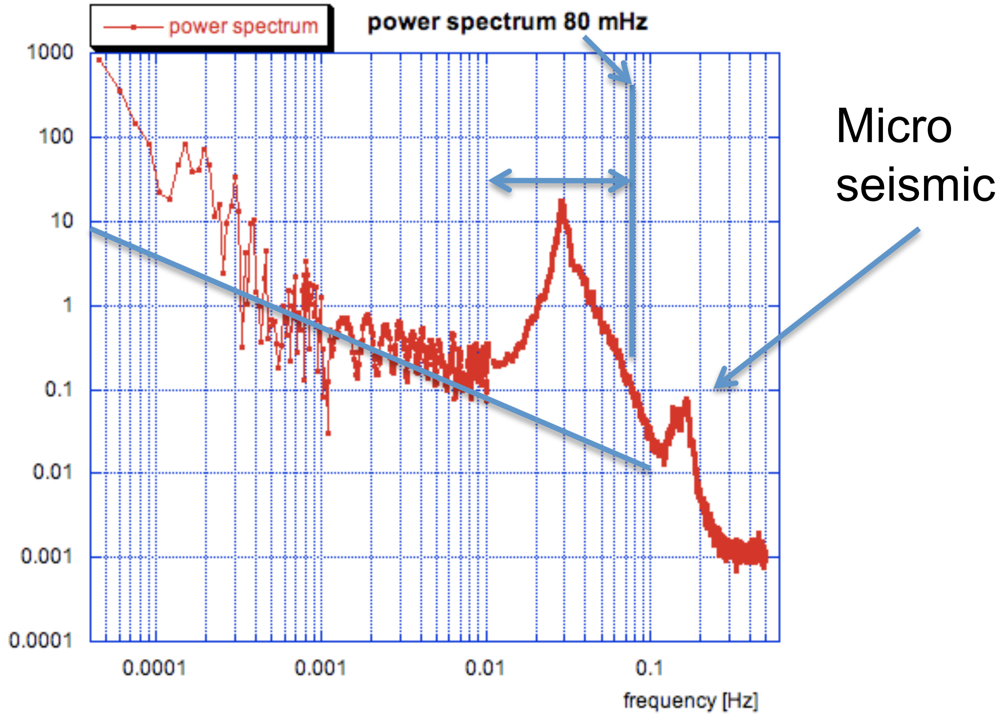
Possible Explanation

- When restoring forces are controlled by entangled dislocation rigidity
- avalanches randomly shift the equilibrium point
- Young's modulus and dissipation fluctuate

- Fractal behavior => 1/f power law

Hysteresis equal noise





Hysteresis advanced by bumps ➔ 1/f noise

During avalanching Young’s modulus decreases

Resonant frequency spread from 80 mHz to 30 mHz and lower

First Conclusions

✓Static hysteresis was the first indicator of something shifting inside the material.

✓Hysteresis, run-offs, changing Young's modulus, the 1/f GAS filter TF, and several other unexpected effects were explained in terms of
SOC dynamics of entangled/disentangled dislocations.

✓ An avalanche dominated 1/f noise is expected at low frequencies.

✓The behavior observed in Maraging blades may actually be typical of most polycrystalline metals at sufficiently low frequencies.

Does avalanching noise affect Virgo

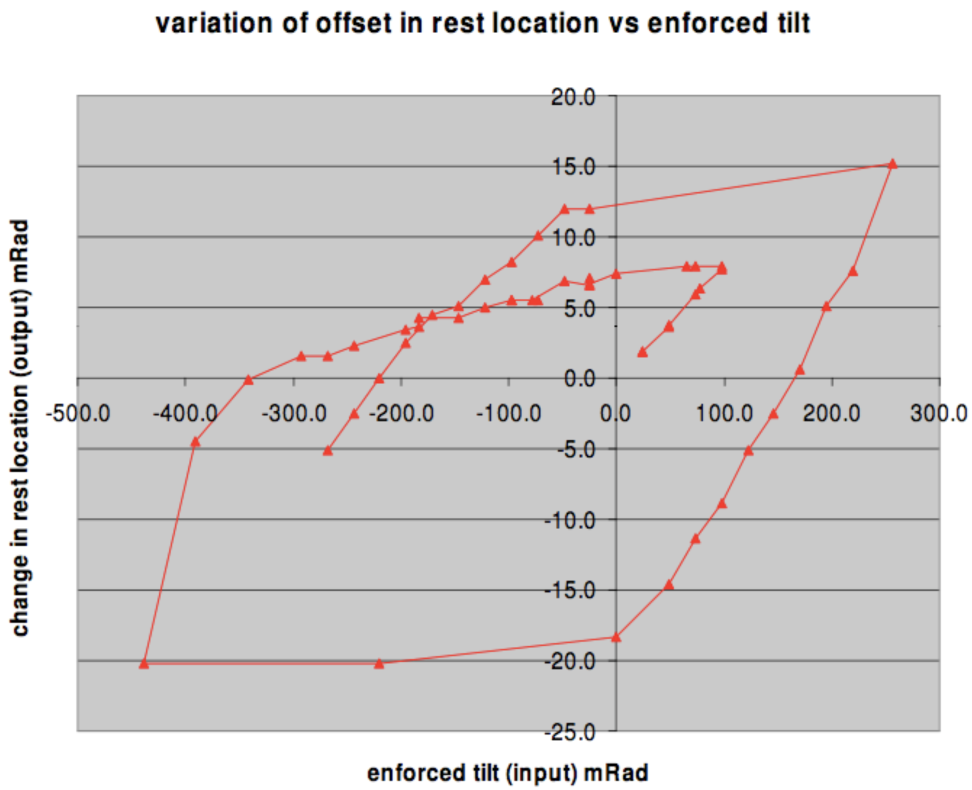
- Inverted pendulum random walk
- Virgo – Tama IP (Takahashi Kyoto presentation)

- Possible noise above the marionetta level percolating into the LF performance
- Well controlled in Virgo (Braccini kyoto presentation)

Will avalanching noise affect Advanced LIGO

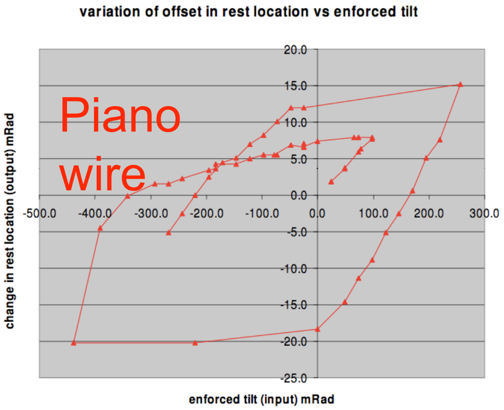
- YES!
- Hysteresis means avalanches!
- Possibly affects even present LIGO

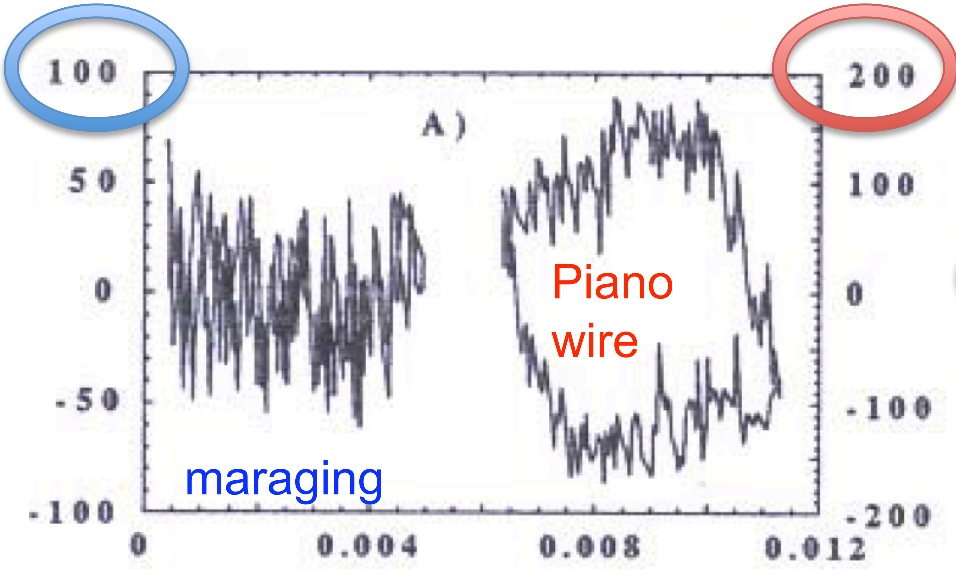
Hysteresis measured in the Advanced LIGO multiple pendulum

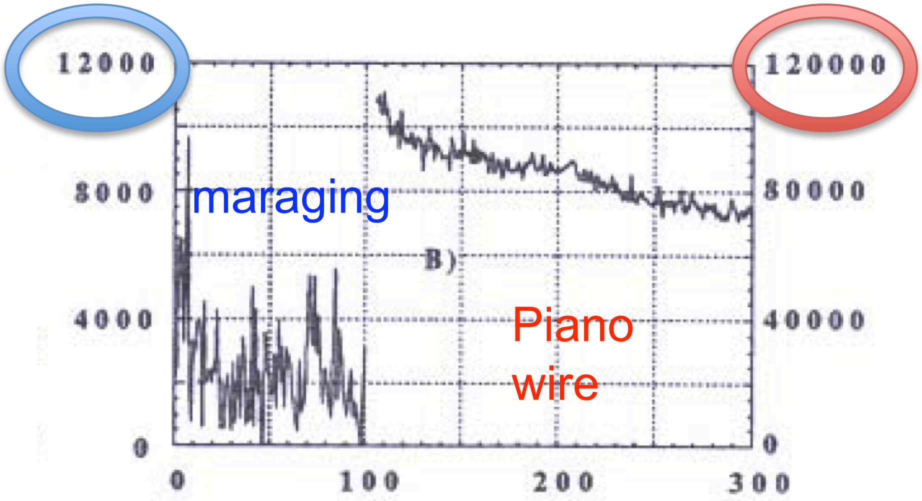


Do the positive Virgo results apply to Advanced LIGO

- Not necessarily



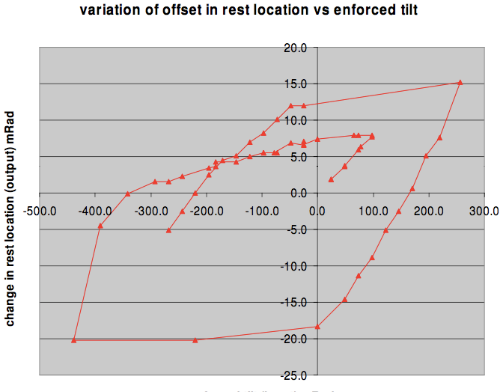




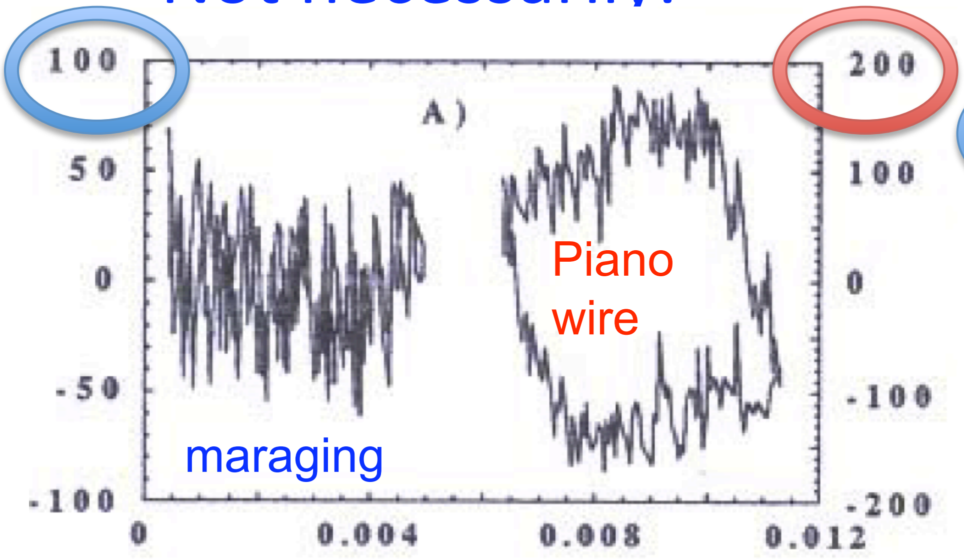
- AdVirgo suspensions are all Maraging
- AdLIGO suspensions are all piano wire

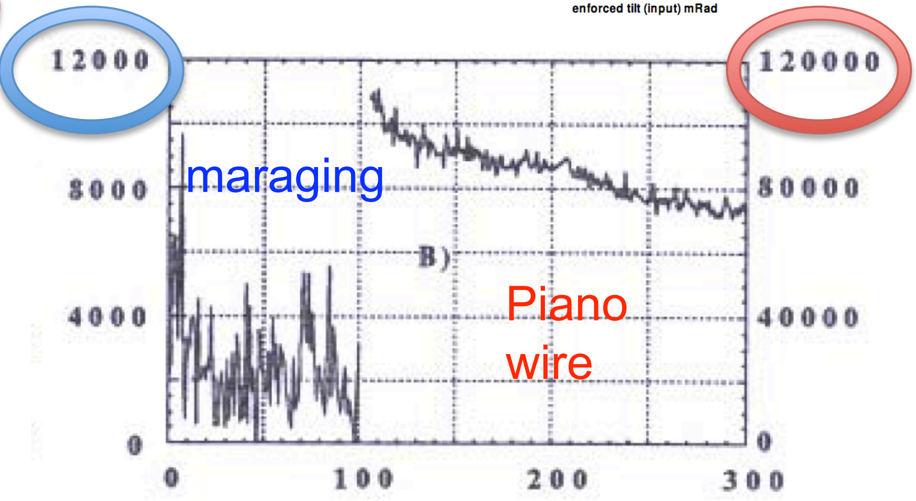
R DeSalvo, "Non stochastic noise in gravitational wave detectors", proceedings of the second Edoardo Amaldi conference, CERN Switzerland, World Scientific , p 228-239, 1997

Do the positive Virgo results apply to Advanced LIGO



- Not necessarily:





- In addition shear clamps, worse possible choice
- Can we avoid or mitigate its effect

T.J. Quinn, et al., “Stress-dependent damping in CuBe torsion and flexure suspensions at stresses up to 1.1GPa.”, Physics Letters A, 197, p 197-208, 1995.

SOC noise is a dynamic effect

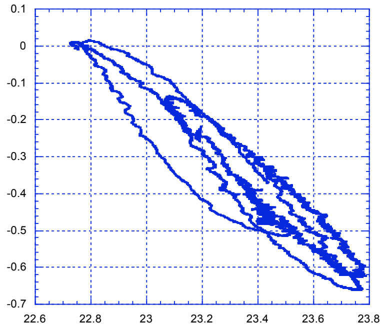
It needs a power source
to generate critical slope

No power source, no SOC noise

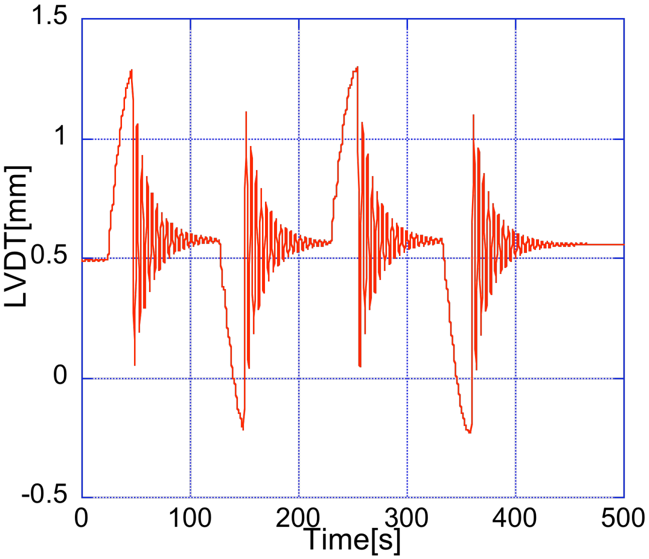
Good practices and palliatives for Advanced Interferometers

- Reduce thermal fluctuations
- Impede slow movements (tidal, etc.)

in the low stages of attenuation chains



- Work at true equilibrium point
  (not a dislocation pattern induced one)
- Periodically flatten the dislocation landscape with forced oscillations



Long term solutions?

- ✓ New materials and processes need to be explored to design the seismic isolation of third generation, lower frequency GW interferometers

- ✓ Glassy materials that do not contain dislocations or
  polar compounds that do not allow dislocation movement
  candidate materials for seismic attenuation filters and inertial sensors

- ✓ Dislocation movement impede fragility
  we want to avoid their movement
- ✓ => fragility may be an unavoidable effect

is there a better solution?

✓Need dislocation for ductility

✓But we need to stop dislocation avalanching

✓There is a better solution . . .

✓Pin the dislocations, stop avalanching

(to be patented)

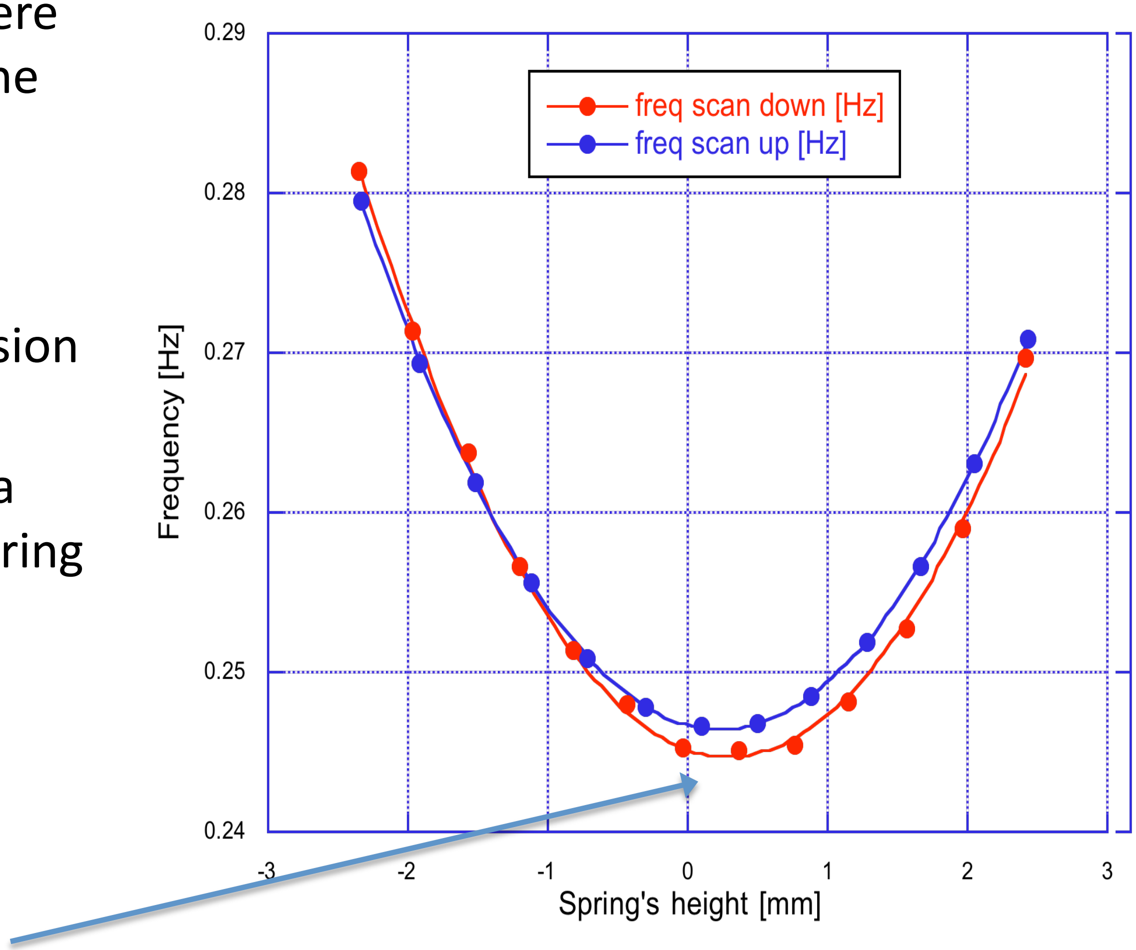
Thank you for your attention

GAS Deviation from linear spring

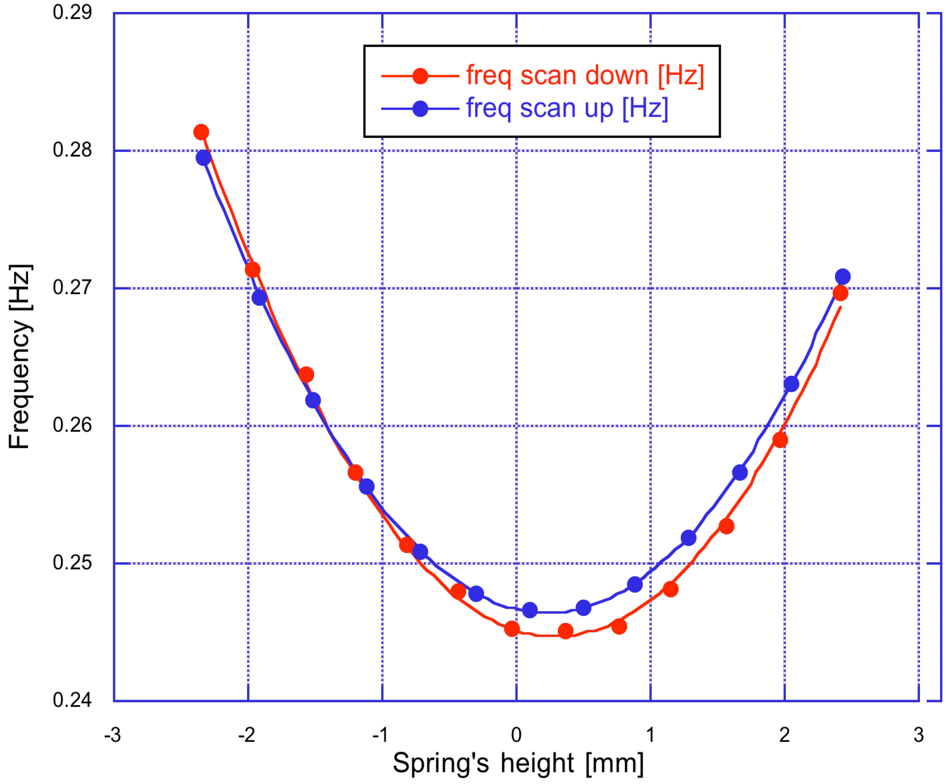
- Calculating the expected frequency shift

Working point

- The GAS mechanism is optimized at the height where the radial compression of the blades is maximized.
- To determine the optimal working point we used the actuator to apply a progression of fixed vertical forces.
- At each height we applied a short pulse to excite the spring and found the oscillation frequency.
- We looked for the minimal resonant frequency (working point).

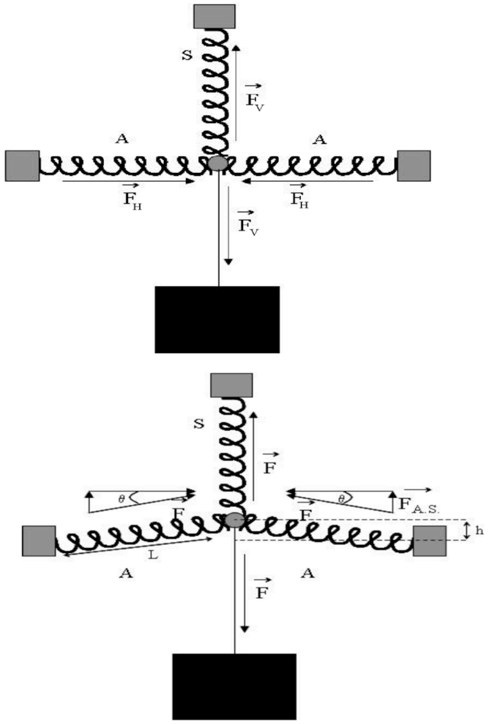


- Larger excitation amplitudes (around the working point), bring the system to explore regions of higher frequency.
- Higher resonant frequencies are expected.



- The GAS spring geometry requires a potential in the form $U = -\frac{1}{2}kx^2 - bx^4$ so that the equation of motion will be

$$m\ddot{x} + kx + cx^3 = 0$$

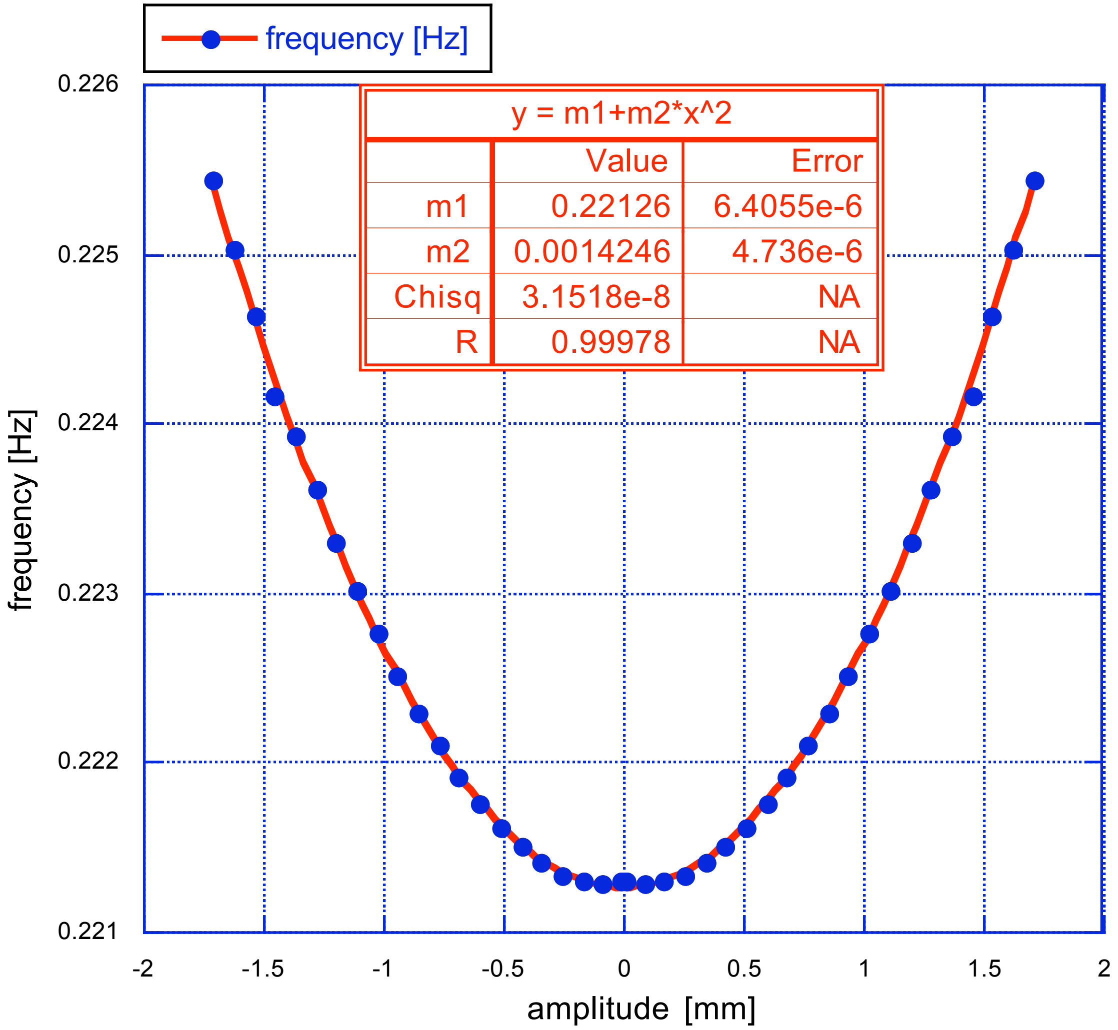


- We solve it numerically, with m=65Kg, k=125 N/m and the coefficient c =2200000 N/m^3 was tuned to match the measured frequency dependence from amplitude

- Then we simulated progressively larger oscillation amplitudes around the working point and monitored the frequency, thus obtaining . . . .

Expected frequency vs. amplitude

Using the parameters of this quadratic fit, we calculated the expected frequency for each of the measured points



y = m1+m2*x^2

	Value	Error
m1	0.22126	6.4055e-6
m2	0.0014246	4.736e-6
Chisq	3.1518e-8	NA
R	0.99978	NA